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Circulation Studies over the Continental Shelf and Slope near the Farallon Islands, CA

EXECUTIVE SUMMARY

by

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Prepared for: Naval Postgraduate School
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Circulation Studies Over the Continental Shelf and Slope Near the Farallon Islands, CA.

A Study Sponsored by the U. S. Environmental Protection Agency and the Western Division, Naval Facilities Engineering Command

EXECUTIVE SUMMARY

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FARALLONES SHELF/SLOPE CIRCULATION STUDIES EXECUTIVE SUMMARY

1. Introduction.

A series of five research cruises were carried out during February, May, August, and November 1991 and February 1992 over the continental shelf and slope in the vicinity of the Farallon Islands, CA. The purpose of the five cruises was to describe the general circulation in the region throughout the year, particularly as it would affect the dispersal of sludge materials to be released at five prospective dumpsites in the area. The approach during each cruise was to occupy a grid of closely spaced conductivity-temperature-depth (CTD) stations across the shelf and slope, while making continuous direct current observations using a hull-mounted acoustic Doppler current profiler (ADCP). The study was funded by the U.S. Environmental Protection Agency (EPA), Region 9, San Francisco, CA, and the Western Division, Naval Facilities Engineering Command (WESTDIV), San Bruno, CA.

The primary instruments used in this study were the Neil Brown Instrument Systems (NBIS) Mark III CTD and the RD Instruments hull-mounted ADCP, operating on a nominal frequency of 150 kHz. The details of the CTD and ADCP calibration procedures are described in the five data reports for the cruises (Jessen et al., 1992a, 1992b, 1992c, 1992d; Rago et al., 1992). The CTD stations all covered the entire water column from surface to bottom. The ADCP data were collected as 3-min averages in 8-m bins using an 8-m pulse length, and reached the bottom or about 350 m, whichever was shallower. The vertical range of the ADCP signal is a function of sea state and varied somewhat from cruise to cruise. Wind data were collected from an anemometer mounted at 10 m height on the ship's mast and from offshore buoys maintained by the National Data Buoy Center (NDBC). The offshore buoys used were located near Bodega Bay to the north, within the Gulf of the Farallones, and near Half-Moon Bay and Monterey Bay to the south.

The basic sampling plan consisted of five parallel transections 20 km apart across the continental shelf and slope near the Farallon Islands (Figure 1). Station spacing was not uniform by design along each transection. Over the steep continental slope, the stations were spaced more closely together to obtain improved estimates of geostrophic velocity in this region. All five lines (labeled A-E) were sampled on all cruises, except for February 1992 when bad weather did not allow sampling along the E line. When time permitted, a separate, continuous ADCP track (solid lines) was steamed at the end of the cruise to gather data uninterrupted by the frequent stopping and turning required for the CTD casts. This track was steamed to various degrees of completion on each cruise, depending on the time available. These tracks were

designated by assigning lowercase letters to the endpoints of each track. While the track locations were consistent, the endpoints were inadvertently given different letters on different cruises. Current meter moorings were also deployed at six locations along the B and D lines as part of this study, and the preliminary results from these instruments are summarized in a separate report (Noble and Ramp, 1992).

Preliminary scientific analyses of each cruise were conducted and forwarded to the funding agencies as unpublished administrative documents along with the data reports. *The purpose of this executive summary is to provide an overview of the collective results from all five surveys.* The wind conditions and regional sea surface temperature are described first, followed by a basic description of the current variability over the continental shelf and slope. This will be followed by a water mass analysis and a comparison with historical data.

2. Climatology of the Gulf of the Farallones, 1991

Meteorological conditions in the Gulf of the Farallones during the 1991 calendar year, when four of the five cruises occurred, were fairly representative of the seasonal cycle off central California (Nelson 1977). These conditions are represented by daily wind vectors, denoting the wind speed and direction at the four NDBC buoys moored off central California (Figure 2) near Bodega Bay (38.2°N, 123.3°W), the Gulf of the Farallones (37.8°N, 122.7°W), Half Moon Bay (37.4°N, 122.7°W), and Monterey Bay (36.8°N, 122.4°W). The wind vectors at the four NDBC buoys were visually coherent throughout the year (Figure 2), with winds at Half Moon Bay and Monterey Bay particularly well correlated. When wind reversals occurred, they typically were observed at all four locations.

Included in the generally coherent wind field, however, are small-scale differences that reflect potentially important variations in mesoscale forcing to the coastal ocean, since they may induce oceanic variability on similar space scales. The wind at the Bodega Bay buoy generally was stronger and directed clockwise relative to that at stations to the south, in agreement with historical studies showing that wind speeds north of Pt. Reyes are stronger than those to the south (Nelson 1977). The change in direction at Bodega Bay is likely due to coastline orientation which tends to steer the winds: the coastline at Bodega Bay is oriented nearly north-south, while the coastline south of Pt. Reyes runs more southeastward. The winds at the Farallones buoy were relatively weaker and directed more eastward than winds measured to the north or south. The fact that much of the Gulf is located in the lee of Pt. Reyes may account for the lower wind speeds observed there. These differences have implications for the location and intensity of upwelling, and the subsequent advection of recently upwelled water along the shelf (Schwing et al. 1991). They also are important in establishing spatial variability in the degree of near-surface

stratification and the generation of shear in the near-surface flow, both of which may play a critical role in driving the region's circulation.

The seasonal variation in the wind was also similar to that reported by earlier authors (Halliwell and Allen, 1987). Winter winds were variable in speed and direction due to the passage of atmospheric cyclones and anticyclones moving onshore from over the Pacific. These conditions persisted until the end of March (day 90) with storm conditions slightly stronger at the northern buoys than at those to the south. In spring and early summer (day 90 to 215), winds were southeastward (upwelling favorable) with only occasional reversals or relaxations. These conditions generally establish an offshore-directed ocean surface current, which results in the upwelling of cool, saline, and nutrient-rich water near the coast. Similar, though weaker, conditions continued through the late summer and fall, pending the onset of the following winter.

Time series of water temperature, air temperature, north wind component, and atmospheric pressure at the Gulf of the Farallones buoy (Figure 3) show the influence of these seasonal changes. The larger variance in atmospheric pressure during the winter and early spring reflects the passage of the winter storms. The air temperature fluctuated about the 10°C mark until about day 140, when seasonal warming and cooling became evident. The sea surface temperature (SST) warmed during the first two months of the year then cooled due to strong upwelling until the beginning of June (day 140) when seasonal heating resumed. Fluctuations with periods of order 10 days, the approximate scale of the wind variability, are evident superimposed on all these seasonal patterns. Increases in the equatorward winds were well correlated with decreases in SST and vice versa (Figure 3). This fundamental upwelling dynamic has been observed by many other investigators (cf. Lentz, 1987).

The shading indicates the dates of the four 1991 cruises (Figures 2 and 3). Moderate upwelling favorable winds were experienced during the February and November cruises. Strong upwelling favorable winds prevailed during the May cruise, and very light winds were experienced during the August cruise. In February 1992 the storm conditions experienced during the cruise (not shown) were quite different from 1991. Winds blew strongly from the southeast as three atmospheric cyclones passed through the area.

3. Satellite sea surface temperature imagery

Satellite AVHRR imagery data for dates during or near the cruises are included to provide information over a larger region than was sampled from the ship (Figure 4). Clear images were available for four of the five cruises, but were not available for the August 1991 cruise, when low clouds and fog prevailed during and for two weeks before and after the cruise. The raw AVHRR data were obtained in digital form from Ocean Imaging, San Diego, CA, and processed

at the Naval Postgraduate School using the University of Miami DSP satellite processing software. The false color scheme to represent SST is the same for each image. The color for each even degree is shown in the temperature scale, while the color changes in the image are at 0.35° C. Within each color the shading goes from dark to light as the temperature increases.

All the images show complex patterns of SST and are rife with mesoscale features over both the shelf and slope. The 15 May thermal image (Figure 4b) shows distinctly cooler surface water than the other three images, a result of strong coastal upwelling during the spring season. A cold filament emanating from the upwelling center to the north of Point Reyes was visible in the 15 May and 2 November (Figure 4c) images. The cooler water showed a bifurcated structure with one branch going offshore into deeper water and the other branch extending southwest along the shelf. While cold filaments off Point Reyes have not been well studied, these features resemble those observed farther to the north off Point Arena during the Coastal Transition Zone (CTZ) experiment (Brink and Cowles, 1991) and to the south off Pt. Año Nuevo (Tracy, 1990) and Pt. Sur (Traganza, et al., 1981; Breaker and Mooers, 1986). Cold filaments were not observed during the February cruises which were times when coastal upwelling was not occurring. The relatively cold water near Point Reyes during February 1992 contrasts with the warmer, poleward flowing water over the slope and was not a result of local upwelling. Wintertime studies off the central coast are sparse, but the wintertime lack of filaments basically agrees with the findings of Kosro et al., (1991). Other features of the imagery will be referred to subsequently to aid in describing the currents and water masses observed in the ADCP and hydrographic data.

4. A description of the current variability over the continental shelf and slope.

ADCP Data.

The ADCP vectors show certain features which were consistent between all five cruises (Figure 5). The shelf currents (inshore of the Farallon Islands) were weaker and more variable than the currents over the continental slope for all five cruises (Figure 5a). The greater directional variability can be attributed to the tidal currents (Noble and Gelfenbaum, 1990) which contribute a greater fraction of the total current variance over the shelf than over the slope. The ADCP sampling was thus biased by the tides as the ship steamed along the cruise track. Some turning of the current vectors over the shelf at approximately tidal time scales can be seen at the inshore end of the B and C lines during Feb. 91 and Feb. 92 (Figure 5a, upper left and lower panel). The data can be used to make an improved estimate of the spatial variability of the tides, but a more sophisticated analysis than is presently available will be required to do this. The shelf

waters within the bight between Point Reyes and Point Montara were also more sheltered from the wind stress, which increased offshore regardless of direction, i.e., the direct forcing by wind was weaker over the continental shelf than over the slope. Since the shelf here is mostly less than 80 m deep, the shelf currents were also more damped by bottom friction than the slope currents. These factors combined to produce the generally weaker currents observed over the shelf.

Vertical shear was generally weak over the Farallones shelf, with bottom currents slightly weaker, but in the same direction as the surface currents. The across- and along-transect velocity for the February and August 1991 *ab* lines, which run parallel to the shore over the shelf (Figure 6) are typical of the magnitude of vertical shear observed. The lack of vertical shear once again suggests domination by the barotropic tides, and differs somewhat from the observations made during the Coastal Ocean Dynamics Experiment (CODE) along a more exposed stretch of coastline between Point Reyes and Point Arena. Wind forcing was more evident there and current reversals with depth were common over the outer shelf, offshore of the 80 m isobath (Winant et al., 1987; Kosro, 1987).

Currents over the slope showed more consistent patterns within each cruise but differed between cruises (Figure 5). The general tendency was for poleward flow over the slope with the exception of the November cruise, when the California Undercurrent[1] was not evident. The currents during February 91, August 91, and February 92 were poleward over almost the entire study area. This may be because the dynamic trough separating the southward California Current flow from the poleward flow inshore (Lynn et al., 1982; Chelton and Kosro, 1987) was located to the west of the study region. High speed (25 - 50 cm s^{-1}) poleward jets were sometimes observed (Figures 5b and 7) which represent the core of the California Undercurrent. These occurred at 75 - 100 m depth in the main thermocline and were shallower than the Undercurrent core observed farther south off Point Sur (Tisch et al., 1992) and off southern California (Lynn and Simpson, 1987). The orientation of the poleward jet varied somewhat from section to section, this being particularly clear at the 75 and 200 m (Figures 5b and c) depths in the August 1991 data. This may have been a result of topographic steering or temporal variability. Meandering of the core was observed during the August cruise. The poleward flows were evident during a variety of surface wind conditions, which were strongly equatorward during February 91, weak during August 91, and strongly poleward during February 92. The

[1] In this summary, no attempt has been made to distinguish the Davidson Inshore Current from the California Undercurrent. While the authors are not claiming that the currents are the same, their characteristic northward flow is called the Undercurrent.

poleward winds during February 92 did enhance the poleward flow near the surface and obscured the subsurface maximum over much of the section.

The May 1991 slope currents were slightly different, in that an alongshore convergence and offshore flow was evident in the 15 - 23 m currents. The convergence weakened with depth (Figure 5b) where the flow tendency was once again towards poleward flow. At 75 m there was equatorward flow in the northwest corner of the study area.

No significant poleward flow was observed during the October-November cruise when the California Undercurrent was absent and the slope currents were predominantly towards the southwest. A weak eddy was centered over the slope near 37° 30' N, 123° 10' W and may have disrupted the flow. The lack of an Undercurrent during this cruise is a subject of continuing investigation.

The classical seasonal signal to the California Undercurrent / Davidson Current has been described by Hickey (1979), Chelton (1984), and Lynn and Simpson (1987). Off central California northward geostrophic velocities over the slope and extending out as far as 100 km have been described year-round, except April, based on CalCOFI data (Wyllie, 1966; Lynn et al., 1982; Lynn and Simpson, 1987; Hickey, 1979). With an assumption of no flow at 500 db, these data suggest that the strongest poleward flow (10-14 cm s^{-1}) should be present during November-January when the speed maximum is located close to the surface. Poleward flow then weakens in February and during March-May nearshore poleward flow may be entirely absent. During June-August, a subsurface maximum of order 2-5 cm s^{-1} centered at 200-300 m depth is suggested. The core of the Undercurrent then strengthens and shoals during September-October.

The data presented here are in partial agreement with this historical scenario. Poleward flow over the slope certainly dominates our results but the observed speeds were greater than suggested by the historical data, as expected when comparing instantaneous, high-resolution values with lower resolution, long-term averaged data. The conditions observed during individual cruises do not mimic the historical seasonal pattern but rather depend more on the wind stress and mesoscale features present at the time, in agreement with observations by Tisch et al. (1992). Perhaps the most interesting contrast is that the classical picture of a surface-trapped equatorward flow overlaying a well-defined poleward undercurrent was never observed in the Farallones data set. The flow direction observed by the ADCP over the slope, while strongly sheared in the vertical, did not change sign over the water column. We speculate, as mentioned earlier, that the equatorward flowing California Current waters must have been located offshore of the study region.

Dynamic Thickness.

The dynamic height method represents an alternative way of examining the velocity field and depicts the fraction of the flow which is in geostrophic equilibrium with the mass field. The dynamic thickness of the 200-500 dbar level was used to study seasonal fluctuations of the California Undercurrent using the CalCOFI data (Chelton, 1984). Currents flow along the dynamic height contours with the dynamic high on the right. The thickness ranged from 38 dyn cm in May 91 to 45 dyn cm in February 92 (Figure 8b). The Undercurrent dominated the circulation pattern in August 91 and February 92, with poleward flow indicated at all stations deep enough to allow the calculation. In May 91, the Undercurrent appeared only over the upper slope, apparently turning offshore along the northern side of the ridge. In February 91, the dynamic thickness was nearly uniform and in November 91, equatorward flow appeared over much of the region, flowing offshore along the dynamic ridge.

These patterns were not unlike flow depicted by the available ADCP vectors at the 200 m depth (Figure 5c). Weak poleward flow was indicated in February, strong, meandering poleward flow in August, and a distinctive offshore turning of the flow in October-November. The meandering flow in August seemed to follow the bottom topography. The ADCP sampling during May 91 and February 92 were not adequate for a rigorous comparison with the dynamic thickness data.

The dynamic thickness of the upper (0-200 dbar) layer (Figure 8a) responded most strongly to coastal upwelling and equatorward acceleration of the California Current. The thickness of this layer ranged from 32 dyn cm in May 91 to 52 dyn cm in February 92. The low dynamic thickness during May indicates the presence of anomalous dense water during this time, and explanations for this are sought in the water mass section. Strong equatorward flow occurred in May and August 91, the former stronger and southeastward, the latter southward. Poleward flow over the survey region was observed in February 92. Gradients were weakest in February and November 91 when there was no clear pattern. Weak eddies seem to be present during these times, one centered near 37° 40' N, 123° 20' W during February and another near 37° 20' N, 123° 25' W during November. The latter eddy was co-located with a weak warm feature in the 2 November SST imagery (Figure 4c).

Unlike the 200 m level, the currents indicated by the dynamic height calculation do not agree well with the ADCP data. The simplest explanation for this is that the geostrophic currents were calculated relative to the 200 dbar level which was clearly not a level surface. The value of the calculation lies in showing the baroclinic contribution to the flow.

Surface Drifters.

Drifting buoys provide a different way of examining the mean and mesoscale motions in the ocean. These "holey-sock" drifters were drogued at 10 m depth, had a very low surface drag area, and represent the flow in the upper mixed layer. Four satellite-tracked drifting buoys (Figure 9) were deployed near 37° 45' N, 123° 30' W, the offshore corner of the study region, one each during the May 91 through February 92 cruises. Positions were determined and transmitted to shore using the ARGOS satellite-based system, which is part of the NOAA polar orbiting satellite system and returns 6-8 fixes per day at 38° north. The May and August buoys each initially moved offshore, then moved southward to around 36° 30' N where they moved onshore about 100 km before resuming their southward path. These paths were quite similar to those observed during the Coastal Transition Zone Experiment (Brink et al., 1991). The fact that the May buoy moved and remained farther offshore than the August buoy is likely due to stronger upwelling and more energetic offshore jets during May than during August. The November buoy initially moved southward before becoming entrained in a series of eddies which transported the drifter far offshore. The February 1992 buoy moved northward and onshore steadily, in agreement with the ADCP vectors from the 15-23 m level (Figure 5a). The strong poleward winds during this time would drive the near-surface current poleward and onshore (downwelling favorable). This is historically the time of the Davidson inshore current, a broad poleward flow over the entire continental shelf and slope. The drifter's reversal to a southward track on day 419 followed a shift to equatorward wind stress.

5. Water Mass Analysis.

T-S Properties

A composite T-S diagram for the five cruises illustrates the observed water mass variability (Figure 10a). Below 4.0°C and greater than 34.5 psu Pacific Common Water is found which has a stable T-S relationship throughout the North Pacific. Mantyla (1980) notes that the natural salinity variation in the deep Pacific north of the equator is only about 0.02 psu; the variability observed in these waters (Figure 10a), about 0.005 - 0.008 psu, is likely due to the accuracy of our salinity calibration techniques.

Between 4.8 and 7.0°C (corresponding to density anomalies of 26.55 and 27.2 kg m^{-3}), contrasting T-S properties associated with Subarctic Intermediate Water (found offshore in the California Current) and Equatorial Water (found over the slope in the California Undercurrent) are found. Horizontal mixing between these water types occurs, resulting in greater variability of salinity along an isopycnal than occurs either in deeper waters or in waters at the base of the halocline. Subarctic waters were associated with one cast, station 49 on 20 May 1992, and the

salinity contrast on this cast was greatest at a density anomaly of 26.75 kg m^{-3}, resulting in a salinity variation of 0.25 psu on this isopycnal for all data. Although the horizontal scale of this intrusion of Subarctic water was not resolved, it is indicative of the active mixing which must occur at these depths in the region of the dump site.

Upper ocean T-S properties are shown in Figure 10b, where the scales of Figure 10a have been expanded to focus on the upper ocean. Although there is a great deal of variability in these waters on a given cruise, variability between cruises can be discerned. The May 1991 cruise is associated with cool, relatively fresh water that appears as a mode from 8.0°C, 33.9 psu to 9.0°C, 33.6 psu. Other data fall along a curve extending from 8.7°C, 34.0 psu to 16.0°C, 34.4 psu. October 1991 and February 1992 data cover about the same domain, extending to about 14.0°C, while February 1991 data are generally cooler than 12.5°C. August 1991 data had the greatest temperature range, extending to 17.2°C, and for temperatures warmer than 10.0°C, the greatest salinity range with the mean about 0.1 psu saltier than other months.

We believe that we observed waters which originated in San Francisco Bay at Stations 19 and 20 in February 1991, at Station 40 in August and at Station 21 in early November (Figure 10b). It is difficult to distinguish these waters, based on T-S properties, from those found offshore. The signature of the water mass boundary between inshore surface waters and surface California Current Waters is that of a horizontal line on the T-S diagram, i.e. along 15.5°C in August and along 13.0°C in February 1992.

Distribution of Upwelled, Offshore, and San Francisco Bay Water

During most of the surveys, near-surface water was some admixture of three primary water types; 1) recently upwelled water, whose source for the Gulf of the Farallones is primarily to the north of Pt. Reyes, 2) offshore water, whose signature is that of the large-scale California Current System, and 3) outflow from San Francisco Bay. These are revealed in the hydrographic surveys and the AVHRR satellite sea surface temperature imagery; the respective sources of these water types are suggested from the shipboard ADCP data. The characteristics and importance of each water type in the Gulf varies seasonally and on shorter time scales.

The May 1991 cruise represents the conditions observed during strong, upwelling favorable winds (Figure 11). The source of the cold, salty, freshly upwelled water was located to the north of Point Reyes, and the coldest, saltiest water (< 9.25°C, > 33.80 psu) was observed in the northeast corner of the sample grid. As suggested by the satellite imagery (Figure 4b) the upwelled water followed two paths southward, one over the shelf and another farther offshore. This water warmed and freshened as it followed these paths, and is seen in the surface plots as the water with temperature < 9.50°C and salinity >33.60 psu. This upwelled water makes a clear

contrast in the surface plots with the offshore water which was both warmer and fresher along the entire offshore boundary of the sample grid. The shape of the isopycnals (Figure 11c) closely followed that of the isotherms and isohalines, and the density increased offshore.

Non-upwelling conditions under calm winds are illustrated by the February 1991 cruise (Figure 12). The coldest water was still in the northeast corner but lacked the accompanying salinity signal characteristic of coastal upwelling. The salinity was nearly isohaline except for the influence of the Bay outflow, particularly at stations 19 and 20 (Figure 12b) where salinities less than 33.00 psu were observed. Water discharging into the Gulf of the Farallones through the Golden Gate is less saline than the water in the Gulf due to the river input into San Francisco Bay. The long-term average salinity at S.E. Farallon Island is 33.4 psu whereas at Fort Point on the south side of the Golden Gate it is 29.9 psu (Peterson et al., 1989). Historically, salinities at both locations are lowest during winter and spring when the delta outflow is the highest. The outflow signal was quite shallow (< 20 m) and was not evident at 75 m depth. Since the Bay outflow was much warmer than the ambient waters, it can also be seen in the SST imagery (Figure 4a). No strong boundaries were present offshore during the February 1991 cruise. The isopycnals followed salinity in the southern half of the grid and increased offshore, but followed temperature and decreased offshore in the northern half of the grid.

The surface salinity plots for the other three cruises are also shown to illustrate the location of the water masses on the T-S plot (Figure 10b) which were quite close in T-S space but geographically separated. The Bay outflow was observed to the north of the Golden Gate during August (Figure 13a), directly off the Golden Gate during November (Figure 13b), and to the south and farther offshore during February 1991 (Figure 12b). There is no obvious explanation for this, but the distribution may be influenced by the prevailing nearshore wind stress. There is likely insufficient volume in the plume to create a true buoyancy driven flow (J. Largier, personal communication). None of the observed plumes extended very far offshore, likely due to the drought conditions presently occurring in the western U.S. The Bay outflow has been observed as far as 64 km offshore in the past (Peterson et al., 1989). The outflow was not observed during May 1991 or February 1992 and this was likely due to the strong wind stress throughout these two cruises that mixed the signal away.

The dominant feature of the February 1992 plot was the strong front offshore of the 1000 m isobath between warm, salty water inshore and colder, fresher water offshore. The strongest signal was in salinity and the front was accompanied by a decrease in density offshore. A similar, but weaker front was observed during the August 1991 cruise (Figure 13a). The waters on the offshore side of these fronts are the water types contained within the dashed circles in Figure 10b, and are well separated geographically from the neighboring Bay waters on the T-S plot. The satellite imagery for February (Figure 4d) shows this front clearly, and its scale

suggests a water mass boundary rather than a mesoscale eddy or filament. This boundary was anomalously close to shore, a possible result of ENSO conditions during February 1992 (see next section).

6. The ENSO Influence and Comparison with Historical Data.

Preliminary analysis of the individual cruises showed that some of the data differed markedly from the historical means. To examine this further, average values of the temperature and salinity were computed at each of the standard depths (20, 80, 200, and 500 m) for the outer slope, inner slope, and outer shelf regions (Table 1, Figure 14) for comparison with the long-term historical means. The outer slope values are averaged over stations 9, 12, and 29; the inner slope values were averaged over stations 14, 26, 27, and 34; and the shelf values were averaged over stations 4, 5, 15, and 17. For comparison, the historical values from Churgin and Halminski (1974) were used for each depth. These represent 50-year averages, but most of the data are from 1950 - 1970. The data are all from offshore of the Farallon Islands and are not shown on the shelf station plot.

The temperature and salinity values at the 500 m level agreed well with the historical values and showed no consistent patterns of deviation. This provides confidence that there were no serious calibration problems with the new Farallones data set. The 20 m level is subject to the vagaries of mixed layer dynamics and short-term variability and is a less robust indicator of interannual variability than the 80 and 200 m levels, but the patterns that emerged there were generally consistent with the deeper levels.

The largest deviations from the historical means occurred during the May cruise when the water was anomalously cold and salty at both the inner and outer slope stations. The largest deviations were at the inner slope stations when the thermal anomalies were -2.30, -1.04, and -0.30 °C at 20, 80, and 200 m respectively. The corresponding salinity anomalies were 0.31, 0.31, and 0.09 psu at the same depths. During August, November, and the following February the water became progressively warmer and fresher in all three regions with the result that in February 1992, the water was anomalously warm and fresh relative to the historical means. The anomalies were similar over the inner and outer slope, but were slightly greater over the inner slope, and greater at 80 and 200 m than near the surface (20 m). The thermal anomalies over the inner slope were 1.02, 1.34, and 1.21 °C at 20, 80, and 200 m respectively. The corresponding salinity anomalies were -0.03, -0.06, and -0.19 psu at the same depths. All three subregions showed the same rather dramatic trend towards warmer, fresher water with time.

The warm, fresh anomalies in February are suggestive of ENSO (El Niño-Southern Oscillation) conditions, consistent with observations in the equatorial Pacific that indicate 1991-

92 as an ENSO year. The existence of larger anomalies subsurface rather than at the surface is consistent with earlier observations in the OPTOMA study area (Rienecker and Mooers, 1986) and elsewhere in the eastern North Pacific (Cole and McLain, 1989). Of particular interest is the negative salinity anomalies, which suggest thermocline depression or anomalous onshore transport of North Pacific Central Water rather than massive poleward advection as the primary mechanism for the anomalous warming. The latter mechanism was thought to be important during the 1982-83 ENSO event (Simpson, 1983, 1984; Lynn, 1983). The cold, salty anomalies during May are harder to understand. The water is always colder and saltier in May than during other times of the year (Figure 14) but not nearly so much as during the 1991-92 year. These water properties can perhaps be explained by cold filaments off Point Reyes which sometimes flow through the northern half of the study region. These filaments contain recently upwelled cold, salty water, and displace the isotherms and isohalines to at least 500 m depth (Ramp et al., 1991; Huyer et al., 1991). The filaments are most common during late May, June, and July, and may influence the long term mean quantities near the Farallones during these months. The unusually strong anomalies during May 1991 would result if filament waters were actually present during sampling. A representative satellite image taken during the May cruise (Figure 4b) indicates that this was the case, as a cold filament is visible in the image crossing the northwest corner of the study area.

These cold, salty anomalies may also be representative of anti-El Niño, or "La Niña" conditions which sometimes precede an El Niño event, although more research is needed to verify this hypothesis. Time series data from the current meter moorings should help determine if this is the case.

7. Conclusions

The hydrographic, ADCP, satellite, and surface drifter data all confirm that the Gulf of Farallones outer shelf and slope region is a dynamically active area. Current and water mass variability was found on time scales covering seasonal (months), oceanic mesoscale (weeks) and meteorological forcing (days) scales. Data from the NDBC Gulf of Farallones buoy (Figures 2 and 3) indicated oceanic response to local windstress variability while satellite data (Figure 4) and water mass variability (Figures 10-13) demonstrated the larger-scale oceanic variability. The southward movement over the shelf of upwelled water from north of Pt. Reyes and the northward flowing Undercurrent over the slope were the two strongest signals in the ADCP (Figures 5-7) and dynamic height (Figure 8) data. The proposed dumpsites are located such that they will be influenced by either of these currents. The absence of these features during some cruises and the presence of numerous mesoscale features in both the water mass distribution and

currents demonstrates that there was no overall dominant pattern to the water column at the proposed dumpsites. It is apparent that the outflow from San Francisco Bay is confined to the inner shelf and does not influence the water column at the dump sites. The drifter data from February 1992 (Figure 9) indicated that in special circumstances surface water from the dumpsite can be transported to the inner shelf in a couple of weeks, but this is not the dominant case.

The combination of these data with the current data from the moored current meter arrays should provide a good estimate of the probable transport of the anticipated dredge material at the proposed outer shelf and slope dump sites.

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TABLES

Table 1 Mean temperature and salinity at four depths for three groups of selected stations representing the outer slope, inner slope and outer shelf portions of the study region. The outer slope values were derived from stations 9, 12, and 29; the inner slope from stations 14, 26, 27, and 34; and the outer shelf from 4, 5, 15, and 17.

TABLE 1

MEAN TEMPERATURE AND SALINITY AT SELECTED DEPTH LEVELS

OUTER SLOPE STATIONS

	20 m		80 m		200 m		500 m	
	Temp	Salinity	Temp	Salinity	Temp	Salinity	Temp	Salinity
Feb 91	12.307	33.296	10.637	33.399	8.507	33.969	5.956	34.21
May	10.777	33.187	9.05	33.636	7.583	34.064	5.473	34.242
August	14.437	33.409	10.112	33.661	8.647	34.004	5.996	34.196
Oct / Nov	13.032	33.303	10.173	33.469	8.508	34.02	5.721	34.196
Feb 92	13.204	33.116	11.868	33.368	8.863	33.947	6.149	34.192

INNER SLOPE STATIONS

	20 m		80 m		200 m		500 m	
	Temp	Salinity	Temp	Salinity	Temp	Salinity	Temp	Salinity
Feb 91	12.117	33.232	11.346	33.453	8.533	33.939	6.097	34.202
May	9.125	33.546	8.54	33.839	7.519	34.097	5.785	34.229
August	13.672	33.423	10.054	33.757	8.932	34.025	6.43	34.202
Oct / Nov	12.315	33.299	9.938	33.532	8.746	33.989	5.798	34.191
Feb 92	13.244	33.183	11.994	33.375	9.366	33.81	6.348	34.186

OUTER CONTINENTAL SHELF STATIONS

	20 m		80 m	
	Temp	Salinity	Temp	Salinity
Feb 91	12.09	33.229	10.865	33.436
May	9.43	33.475	8.21	33.915
August	13.352	33.399	10.057	33.686
Oct / Nov	12.415	33.352	10.357	33.578
Feb 92	13.414	33.268	12.424	33.342

LIST OF FIGURES

flowing towards. The scale for all five plots is the same, and is indicated in the lower right corner of each panel. The units are cm s^{-1}.

Figure 5b As in Figure 5a, except the vectors are from 71-79 m depth.

Figure 5c As in Figure 5a, except the vectors are from 199-207 m depth.

Figure 6 Along (left panels) and across (right panels) transect flow along ADCP survey line *ab* during the February 1991 (top panels) and August 1991 (bottom panels) surveys. Contours are drawn every 5 cm s^{-1}. A positive sign indicates northward and onshore flow for the along- and across-transect velocity sections, respectively.

Figure 7 Across-transect velocity through Section A during August 1991 and Section B during February 1992. Contours are every 5 cm s^{-1} with positive flow into the page (poleward) and negative flow out of the page (equatorward). Strong jets of poleward flow centered near 100 m depth are clearly visible in both panels.

Figure 8 Dynamic thickness of the a) 0 to 200 dbar layer and b) 200 to 500 dbar layer for each of the five Farallones cruises. The contour intervals are in units of 1 dynamic cm. Assuming the lower boundary is a level surface (constant geopotential), the baroclinic currents would flow with greater dynamic thickness on the right, and arrows on the plots have been drawn accordingly.

Figure 9 Drift paths of the four ARGOS-tracked surface buoys deployed during the Farallones cruises. The buoys had 8-m long "holey sock" drogues centered near 10 m, and thus represent the flow in the upper mixed layer of the ocean. The numbers on the plot indicate the position of each drifting buoy in Julian days from January 1, 1991. The symbols used to plot each float are: launched 20 May 1991 - triangles, launched 16 August 1991 - dots, launched 1 November 1991 - crosses, and launched 11 February 1992 - diamonds.

Figure 10a Composite T-S diagram using the temperature and salinity data from all five cruises. Symbols represent the five different cruises as indicated in the legend. The features of this plot are discussed in the text.

Figure 10b As in Figure 10a, with the scale expanded to more clearly reveal the T-S structure of the upper ocean. The solid circles indicate the San Francisco Bay outflow water during February 1991, August 1991, and October-November 1991, and the dotted circles indicate the cold, fresh water located offshore during August 1991 and February 1992.

Figure 11 Near-surface a) temperature, b) salinity, and c) density fields, for the May 1991 cruise. Contour intervals are in 0.25 °C, 0.10 psu, and 0.10 kg m^{-3} respectively.

Figure 12 Near-surface a) temperature, b) salinity, and c) density fields, for the February 1991 cruise. Contour intervals are in 0.25 °C, 0.10 psu, and 0.10 kg m^{-3} respectively.

Figure 13 Near-surface salinity field from a) August 1991, b) November 1991, and c) February 1992. Contour intervals are in units of 0.10 psu.

Figure 14 Average values of temperature and salinity computed for each cruise at each of the standard depths (20, 80, 200, and 500 m) over the continental slope and at 20 and 80 m over the outer continental shelf (open symbols), and historical mean values for each month at the same levels (solid symbols). The historical values are from the atlas of Churgin and Halminski, 1974. The numerical values for each point are also shown in Table 1. The waters were anomalously cold and salty during May 1991 and were anomalously warm and fresh during February 1992.

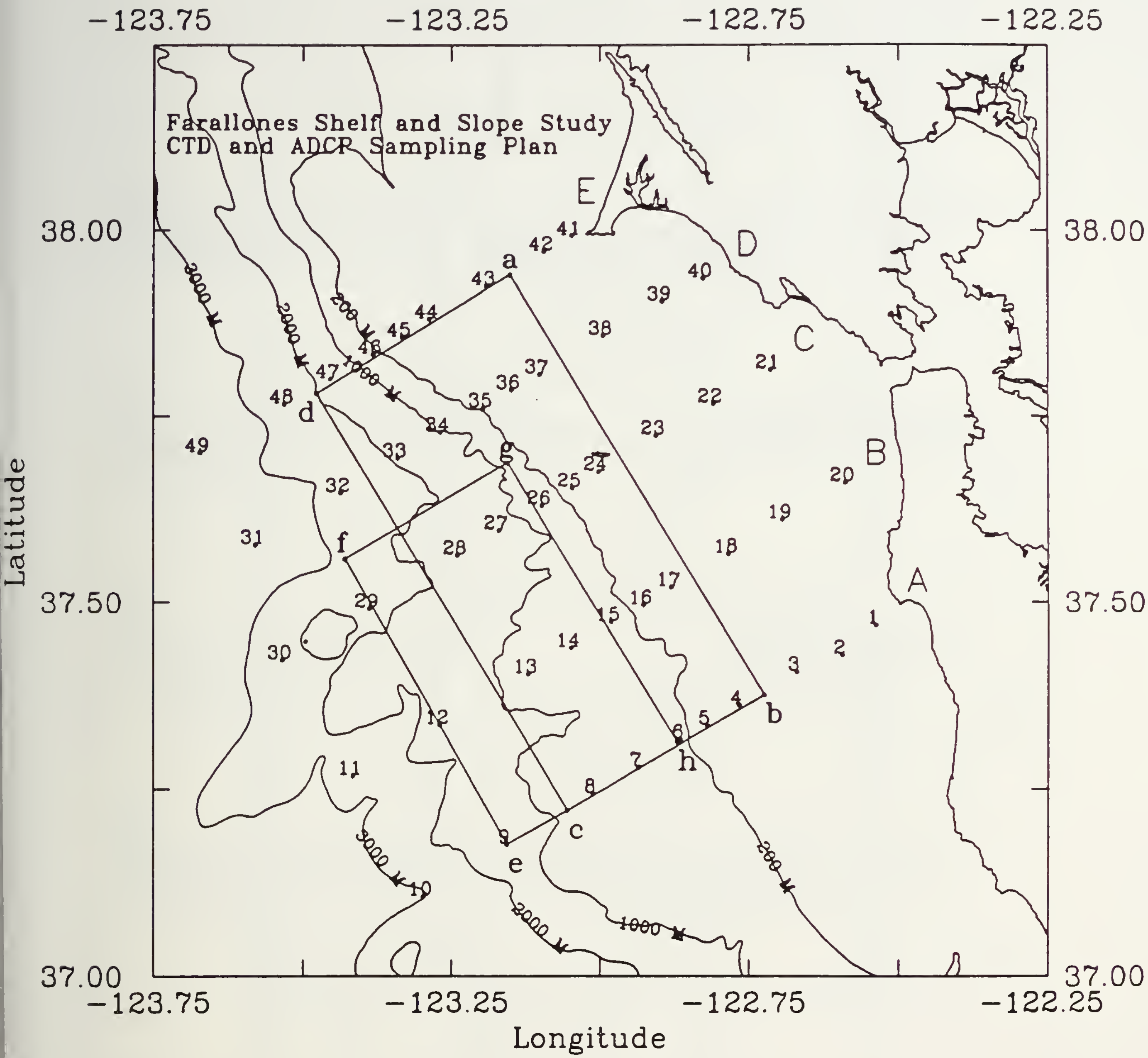

Farallones Shelf and Slope Study
CTD and ADCP Sampling Plan
−123.75
−123.25
−122.75
−122.25
38.00
37.50
37.00
Latitude
Longitude
A
B
C
D
E
a
b
c
d
e
f
g
h
3000
2000
1000
200

Figure 1.

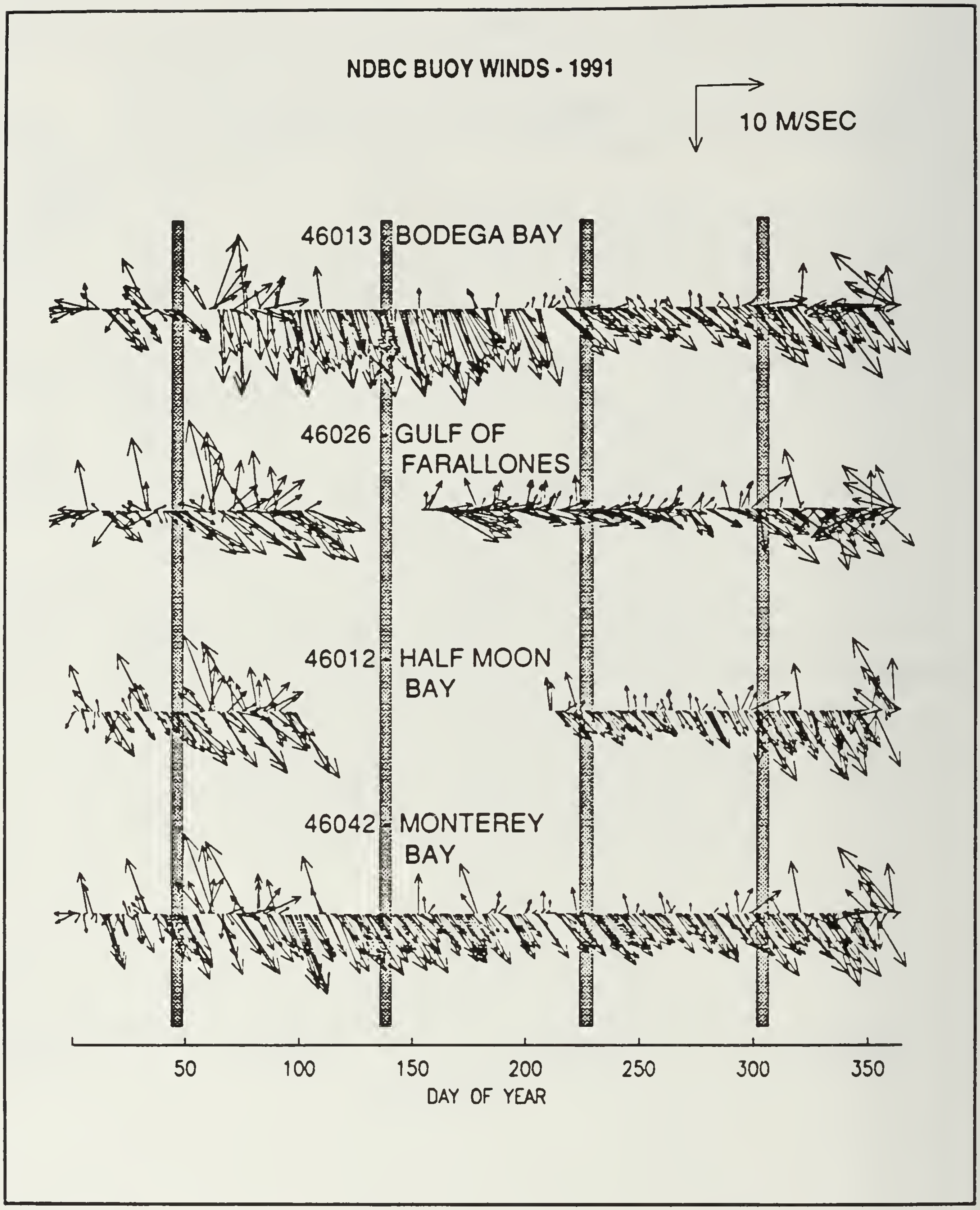

NDBC BUOY WINDS - 1991
10 M/SEC
46013 - BODEGA BAY
46026 - GULF OF FARALLONES
46012 - HALF MOON BAY
46042 - MONTEREY BAY
50
100
150
200
250
300
350
DAY OF YEAR

Figure 2.

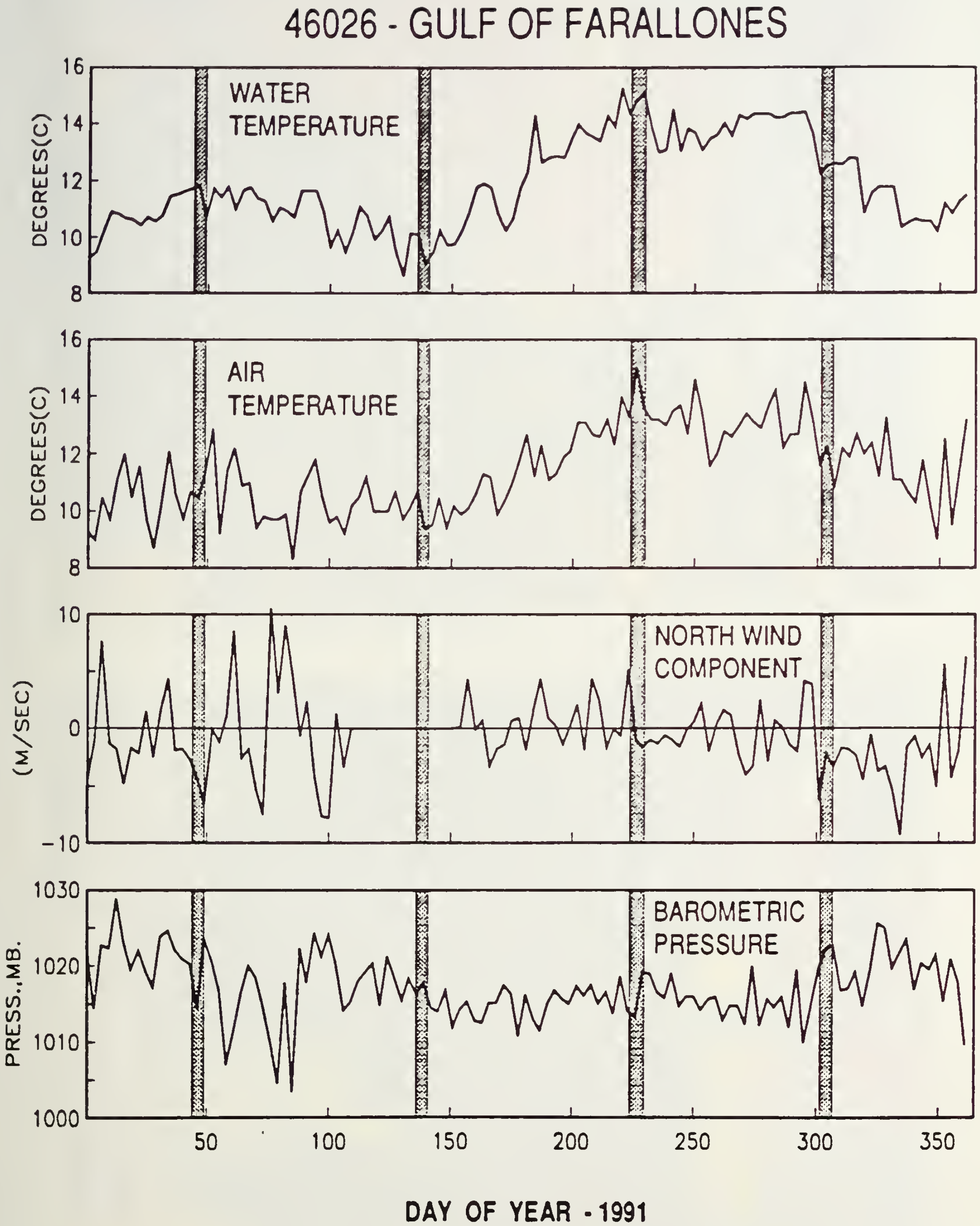
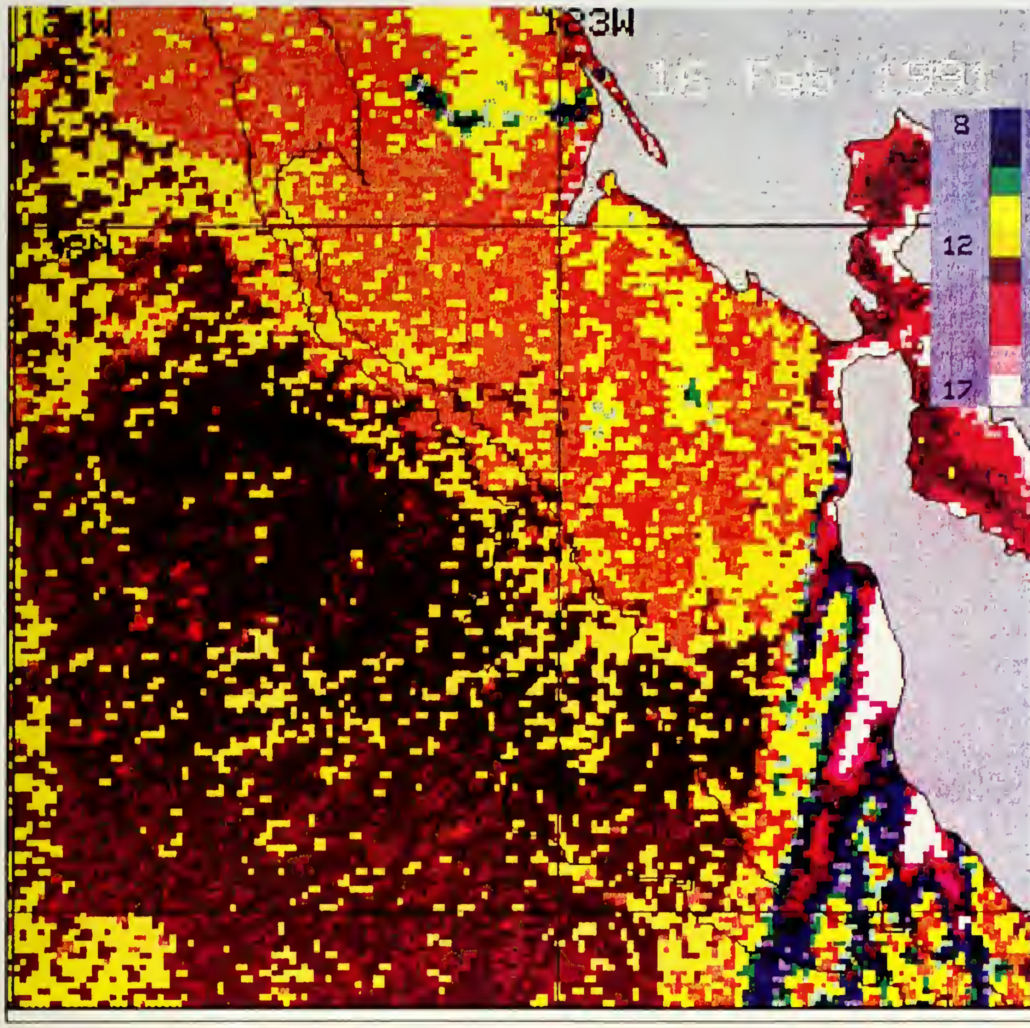
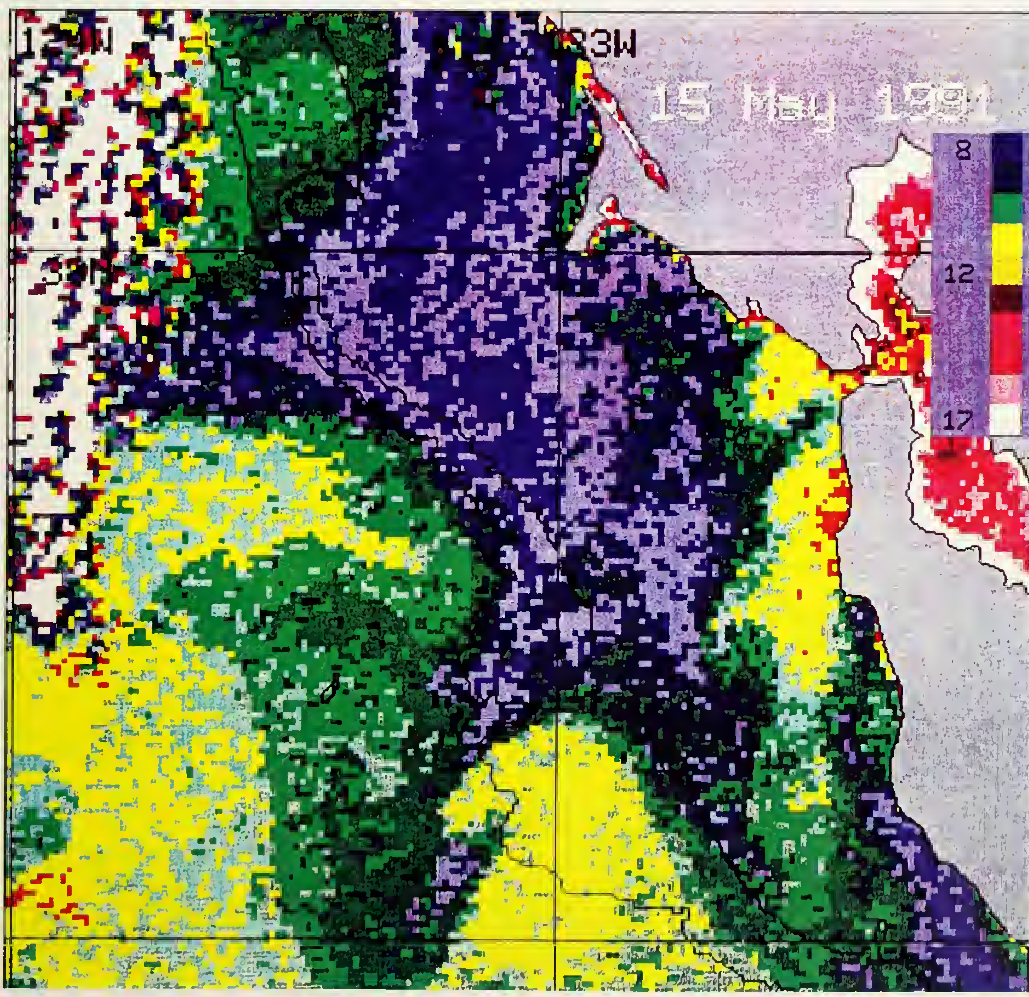

46026 - GULF OF FARALLONES
WATER TEMPERATURE
DEGREES(C)
16
14
12
10
8
AIR TEMPERATURE
DEGREES(C)
16
14
12
10
8
NORTH WIND COMPONENT
(M/SEC)
10
0
-10
BAROMETRIC PRESSURE
PRESS.,MB.
1030
1020
1010
1000
50
100
150
200
250
300
350
DAY OF YEAR - 1991

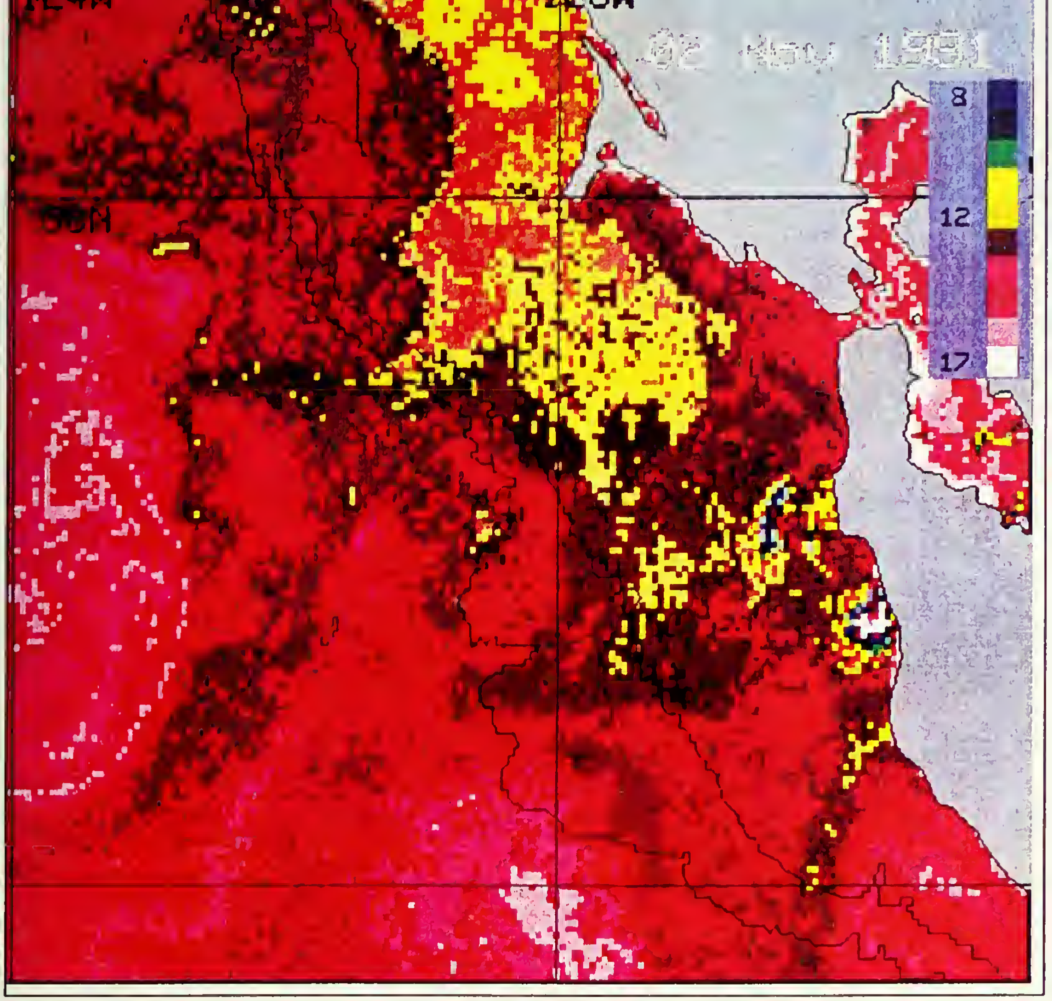
Figure 3.



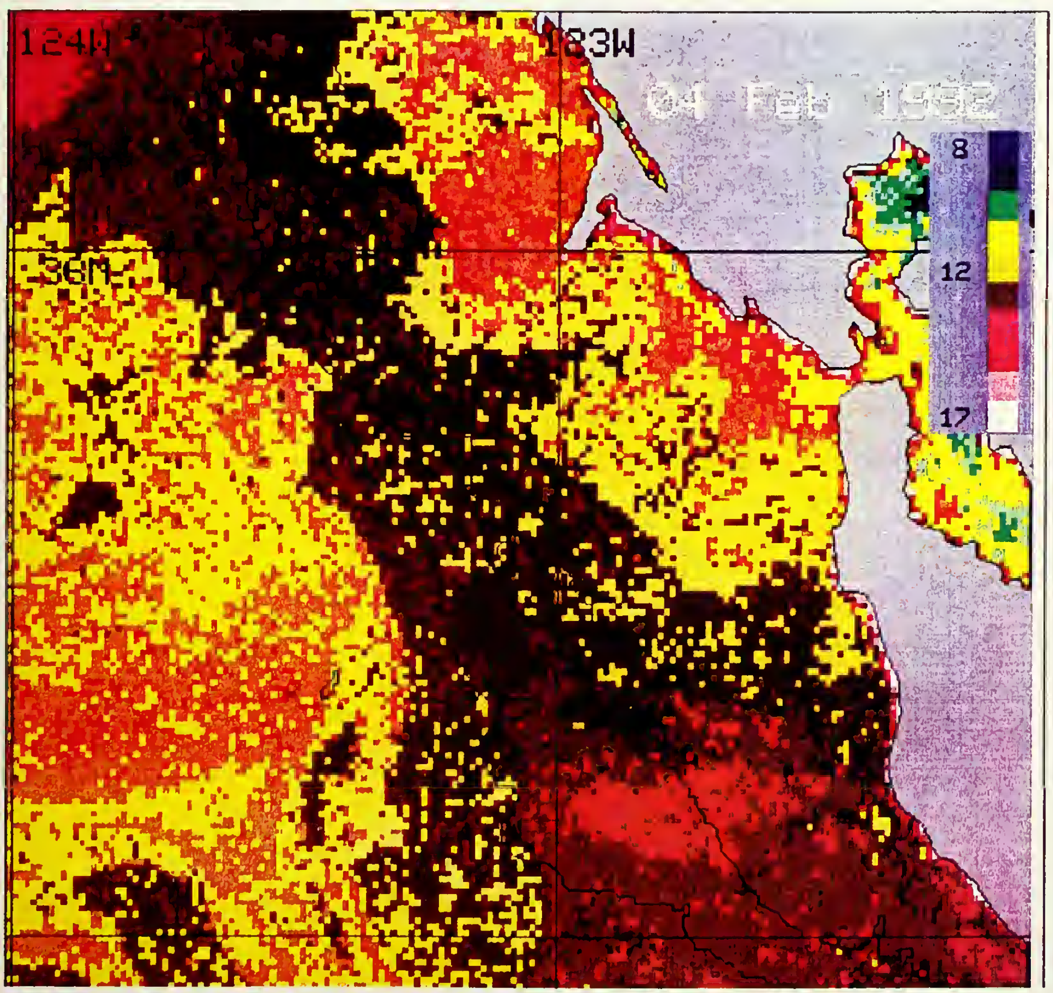
iure 4.a.



,ure 4.b.



igure 4.c.



igure 4.d.

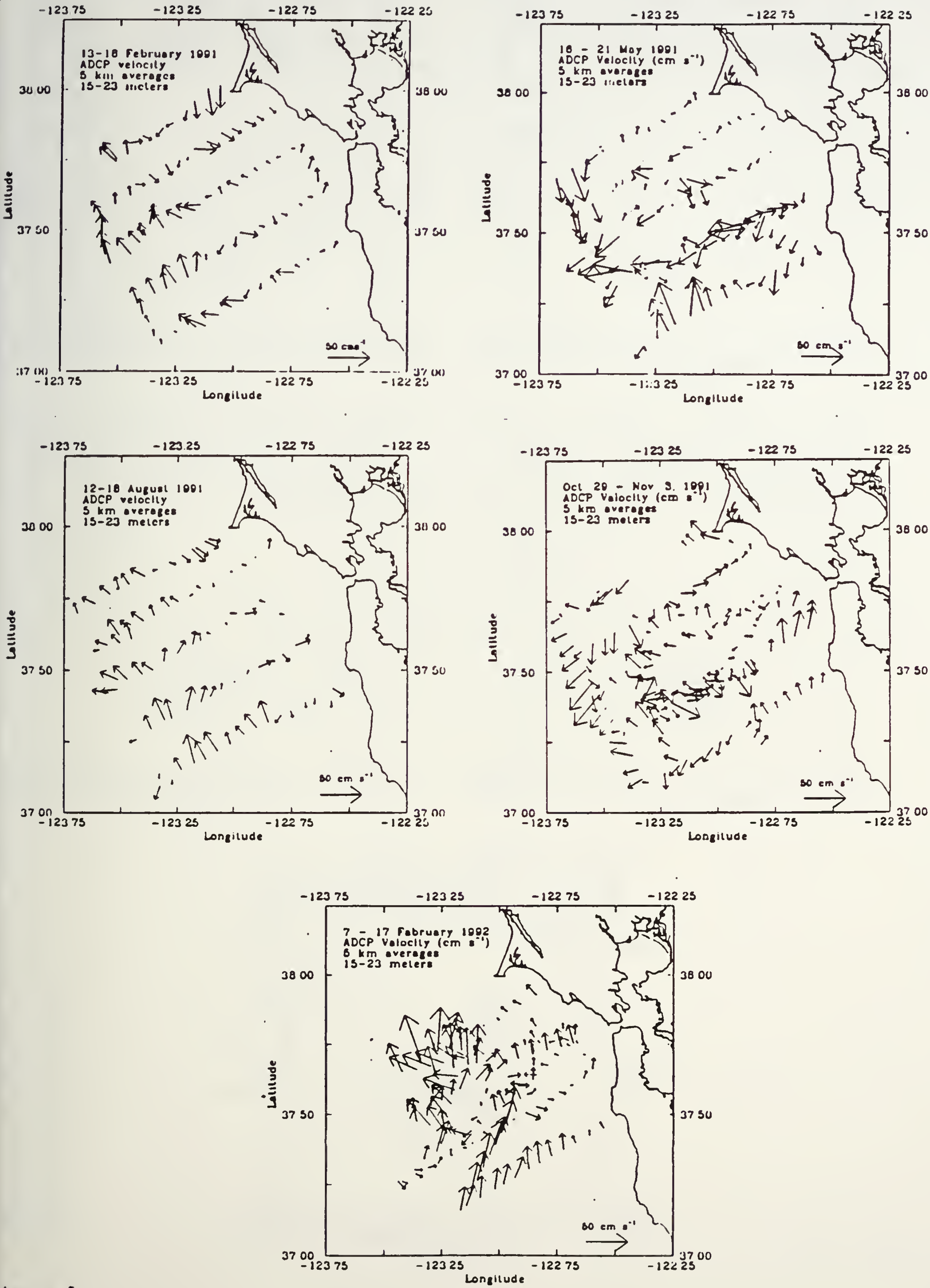
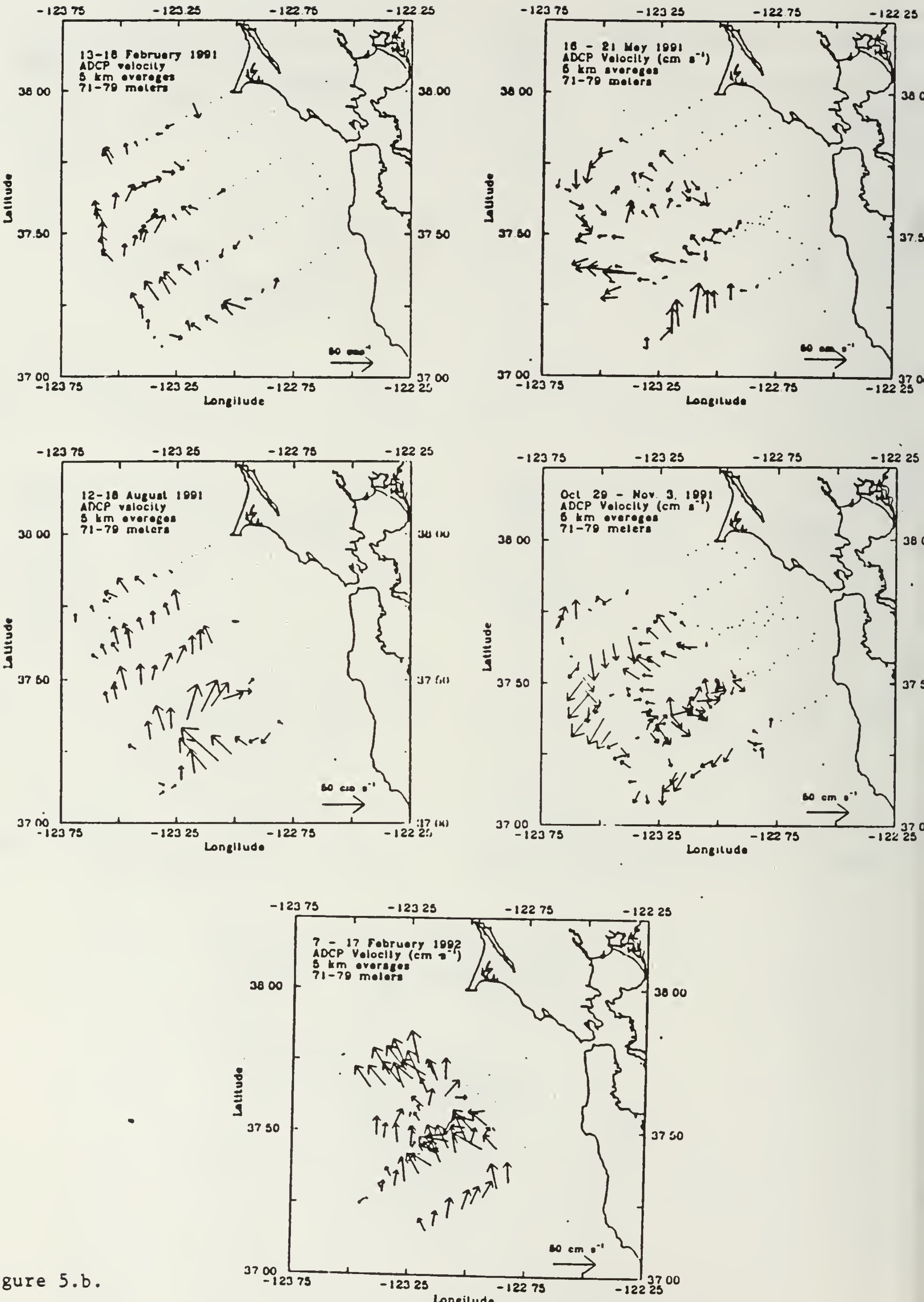

13-18 February 1991
ADCP velocity
5 km averages
15-23 meters
50 cm s⁻¹
16 - 21 May 1991
ADCP Velocity (cm s⁻¹)
5 km averages
15-23 meters
50 cm s⁻¹
12-18 August 1991
ADCP velocity
5 km averages
15-23 meters
50 cm s⁻¹
Oct 29 - Nov 3, 1991
ADCP Velocity (cm s⁻¹)
5 km averages
15-23 meters
50 cm s⁻¹
7 - 17 February 1992
ADCP Velocity (cm s⁻¹)
5 km averages
15-23 meters
50 cm s⁻¹
Latitude
Longitude
-123 75
-123 25
-122 75
-122 25
38 00
37 50
37 00

Figure 5.a.


13-18 February 1991
ADCP velocity
5 km averages
71-79 meters
16 - 21 May 1991
ADCP Velocity (cm s⁻¹)
5 km averages
71-79 meters
12-18 August 1991
ADCP velocity
5 km averages
71-79 meters
Oct 29 - Nov. 3, 1991
ADCP Velocity (cm s⁻¹)
5 km averages
71-79 meters
7 - 17 February 1992
ADCP Velocity (cm s⁻¹)
5 km averages
71-79 meters
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-123.25
-122.75
-122.25
38.00
37.50
37.00
Latitude
Longitude

Figure 5.b.

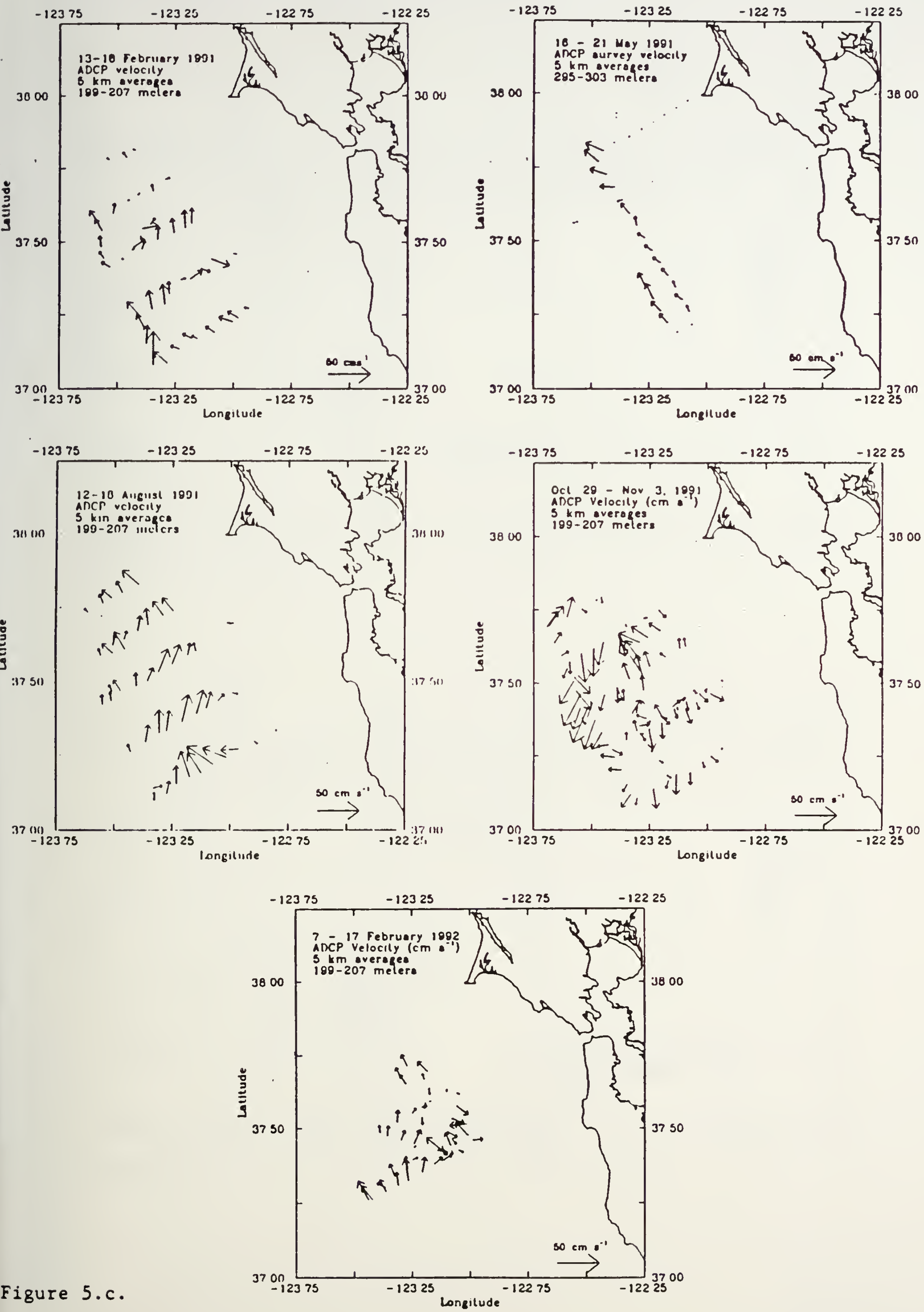

13-18 February 1991
ADCP velocity
5 km averages
199-207 meters
18 - 21 May 1991
ADCP survey velocity
5 km averages
295-303 meters
12-18 August 1991
ADCP velocity
5 km averages
199-207 meters
Oct 29 - Nov 3, 1991
ADCP Velocity (cm s⁻¹)
5 km averages
199-207 meters
7 - 17 February 1992
ADCP Velocity (cm s⁻¹)
5 km averages
199-207 meters
50 cm s⁻¹
Latitude
Longitude
-123 75
-123 25
-122 75
-122 25
38 00
37 50
37 00

Figure 5.c.

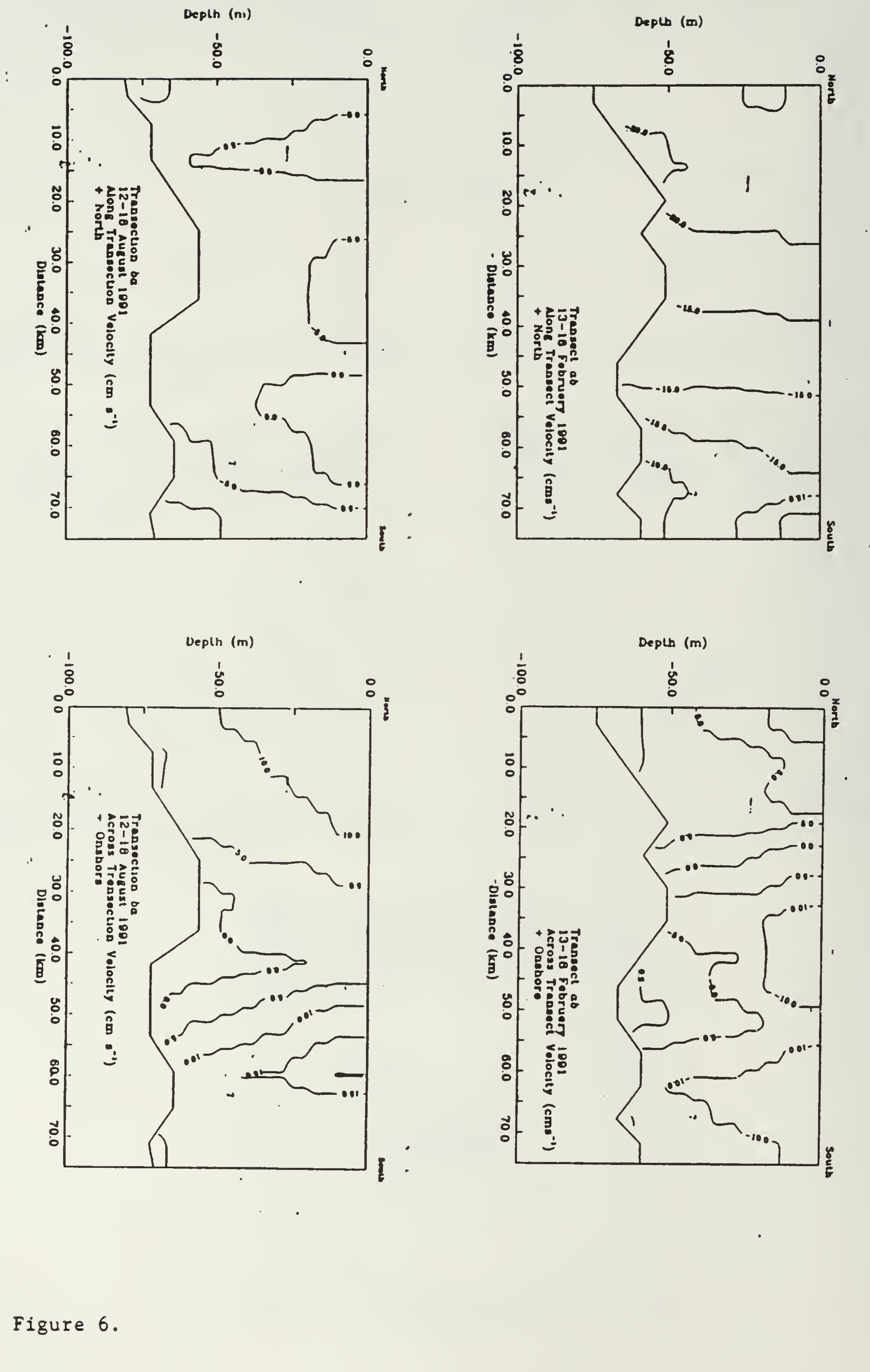

Transect ab
13-18 February 1991
Along Transect Velocity (cms⁻¹)
+ North
Depth (m)
Distance (km)
North
South
Transection ba
12-18 August 1991
Along Transection Velocity (cm s⁻¹)
+ North
Transect ab
13-18 February 1991
Across Transect Velocity (cms⁻¹)
+ Onshore
Transection ba
12-18 August 1991
Across Transection Velocity (cm s⁻¹)
+ Onshore

Figure 6.

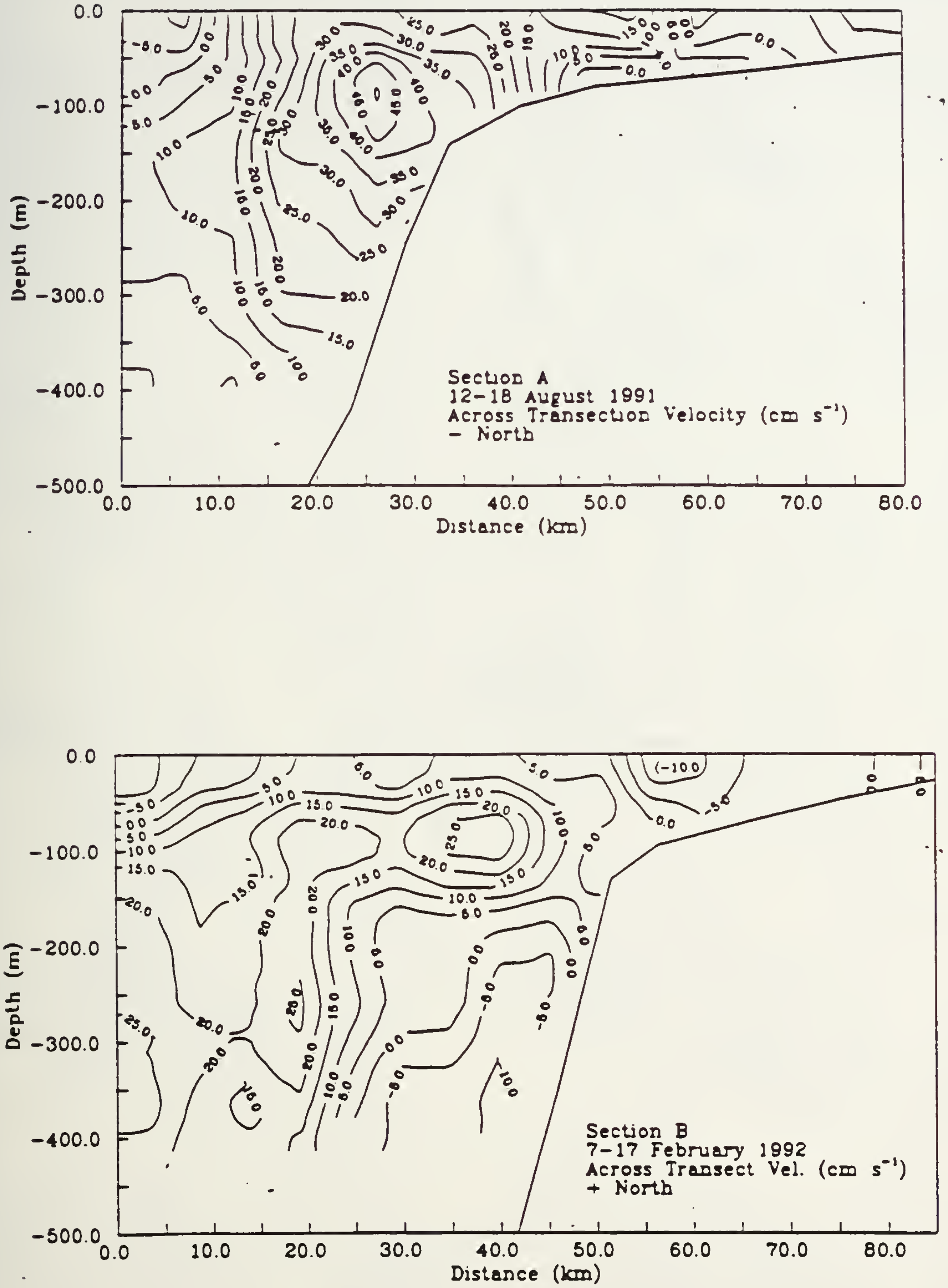

Section A
12-18 August 1991
Across Transection Velocity (cm s⁻¹)
- North
Depth (m)
Distance (km)
Section B
7-17 February 1992
Across Transect Vel. (cm s⁻¹)
+ North
Depth (m)
Distance (km)

Figure 7.

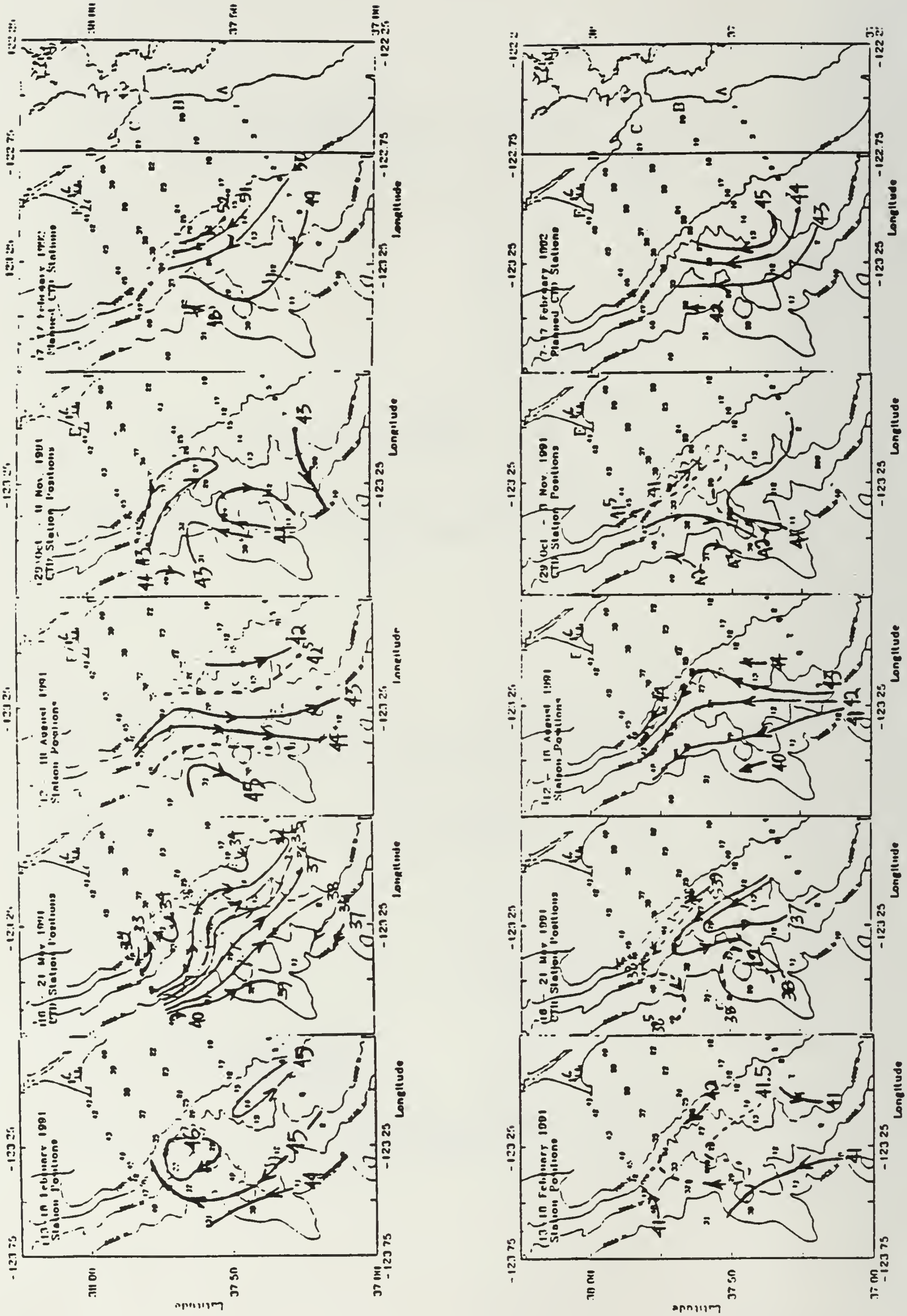


Figure 8.

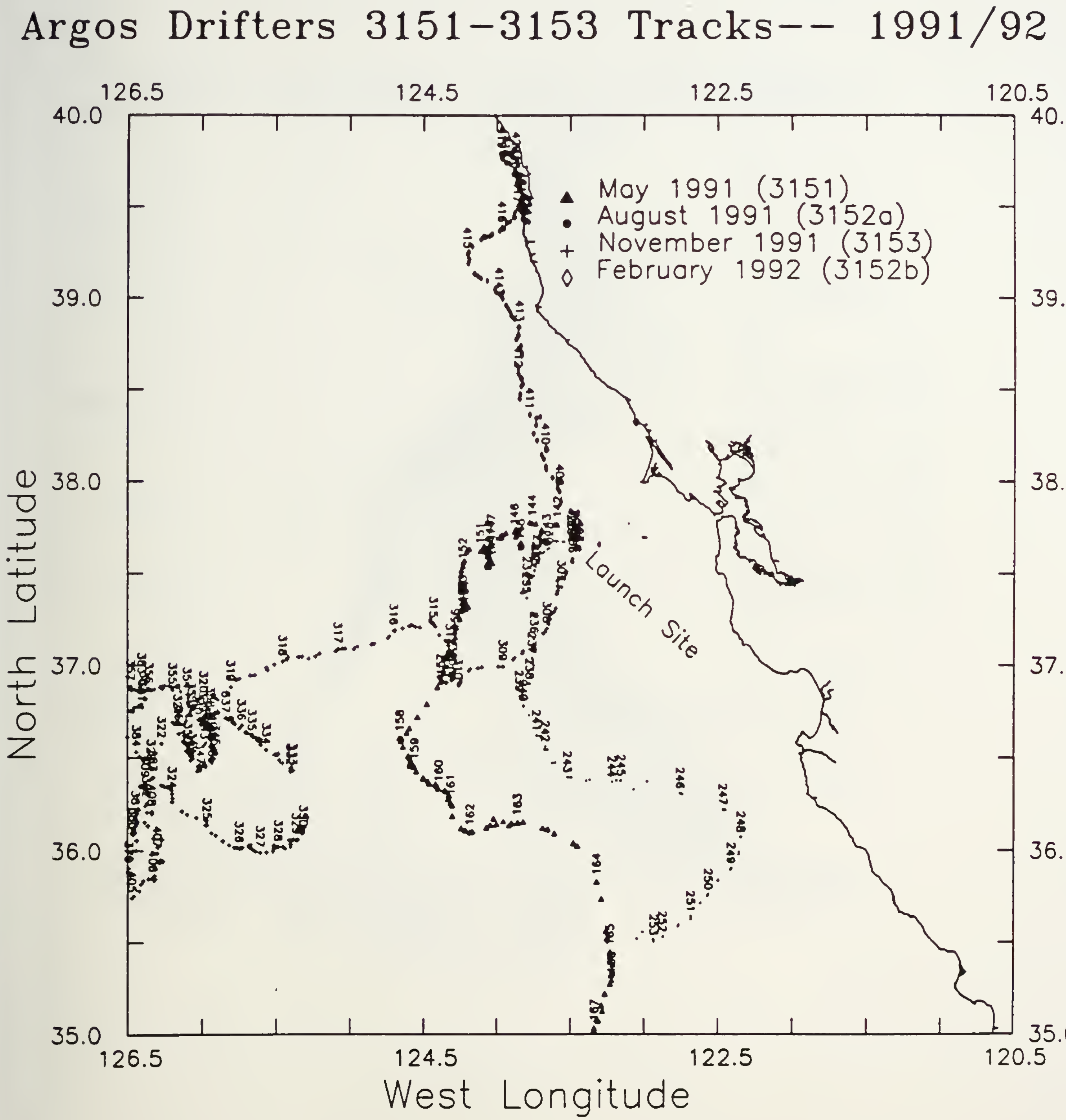

Argos Drifters 3151-3153 Tracks-- 1991/92
126.5
124.5
122.5
120.5
40.0
39.0
38.0
37.0
36.0
35.0
North Latitude
West Longitude
May 1991 (3151)
August 1991 (3152a)
November 1991 (3153)
February 1992 (3152b)
Launch Site

Figure 9.

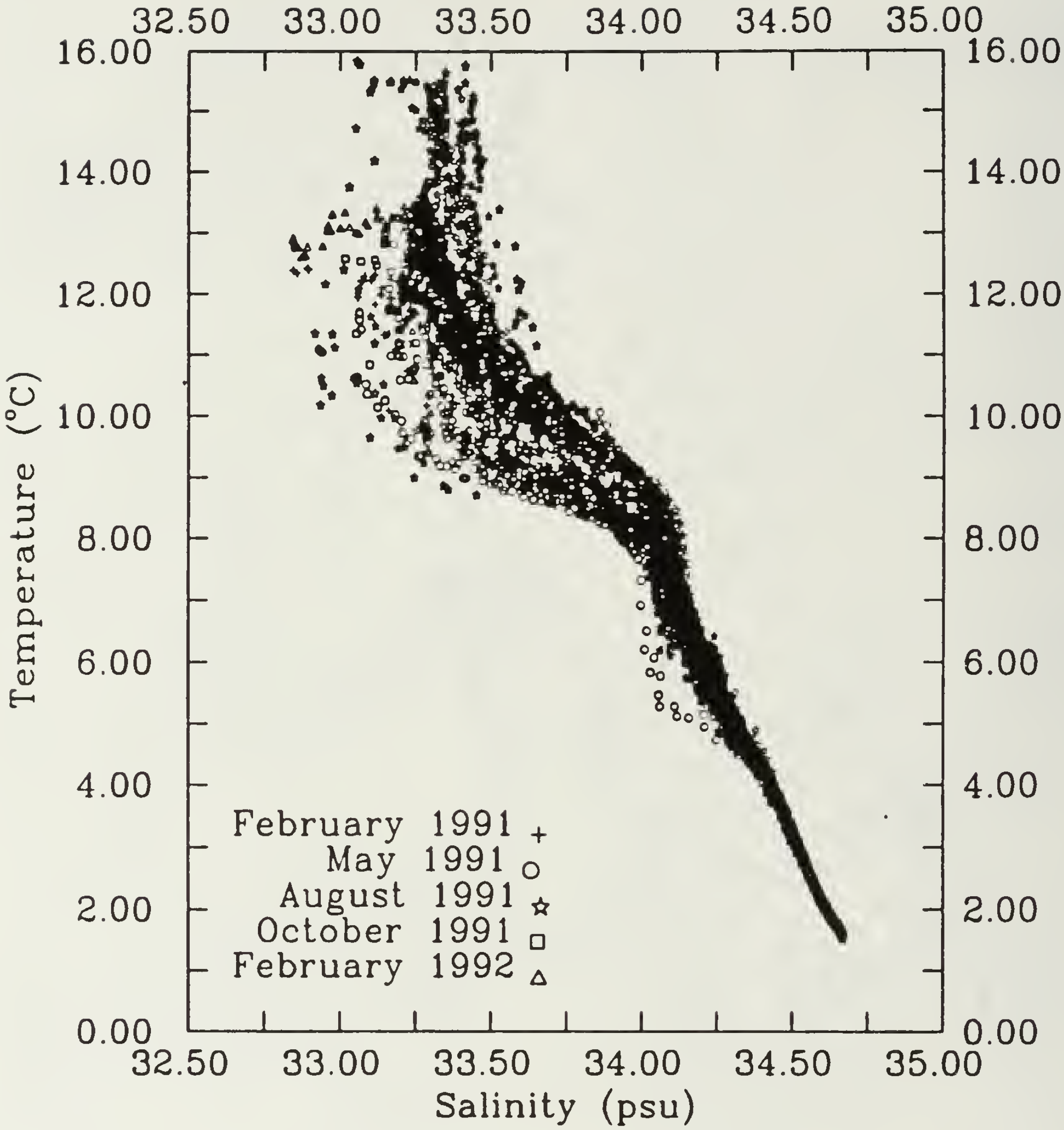

32.50
33.00
33.50
34.00
34.50
35.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Temperature (°C)
Salinity (psu)
February 1991
May 1991
August 1991
October 1991
February 1992

Figure 10.a.

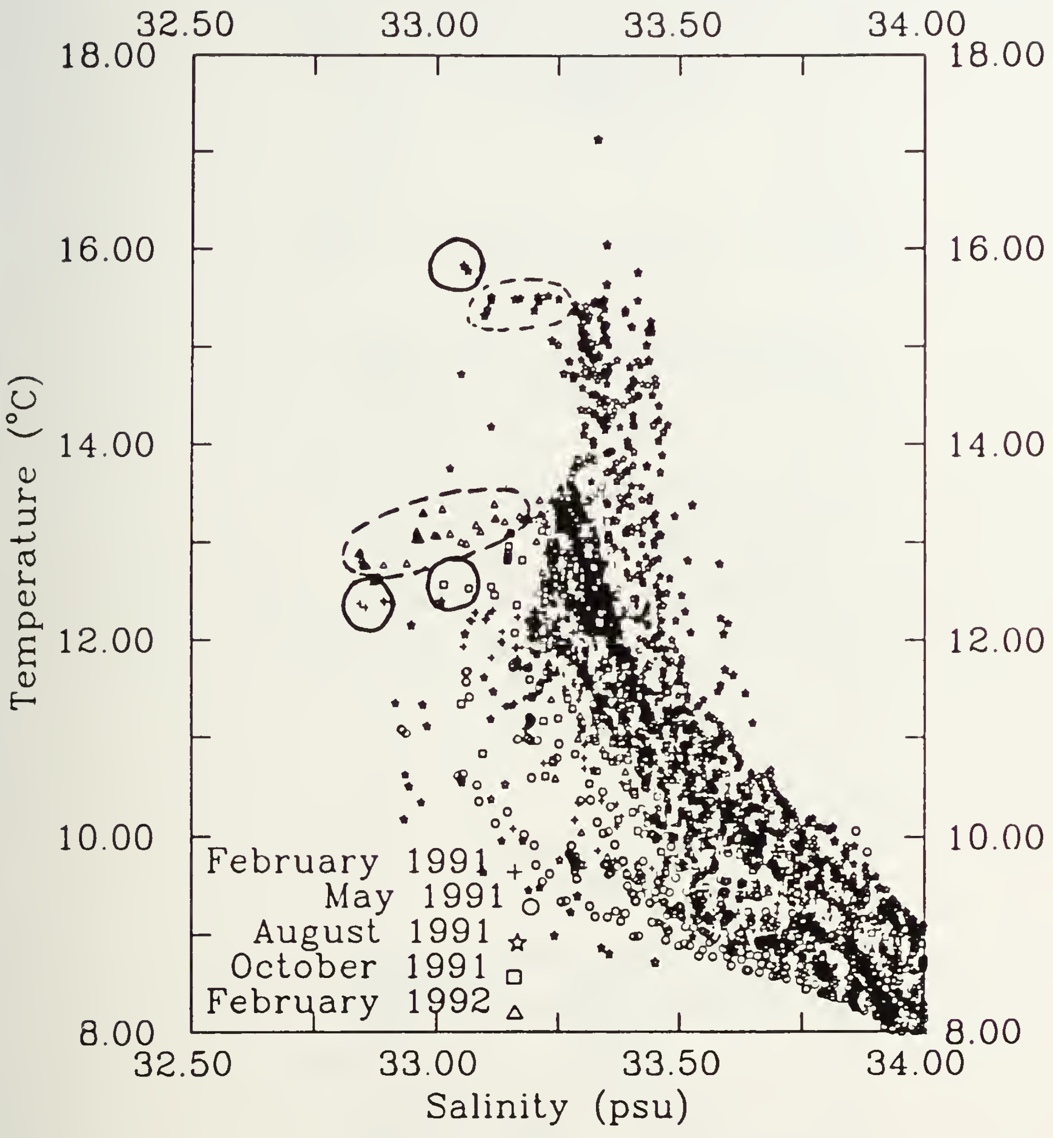

32.50
33.00
33.50
34.00
18.00
16.00
14.00
12.00
10.00
8.00
Temperature (°C)
Salinity (psu)
February 1991 +
May 1991 o
August 1991 ☆
October 1991 □
February 1992 △

Figure 10.b.

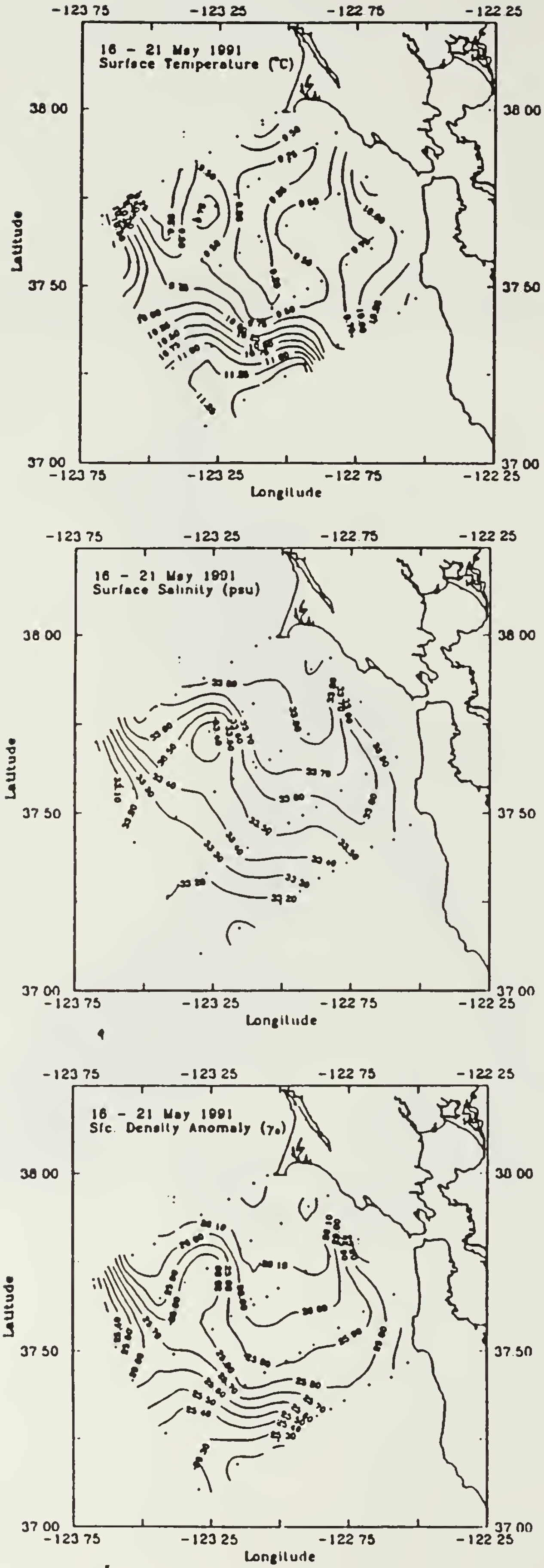

16 - 21 May 1991
Surface Temperature (°C)
16 - 21 May 1991
Surface Salinity (psu)
16 - 21 May 1991
Sfc. Density Anomaly (γ_0)
Latitude
Longitude
-123 75
-123 25
-122 75
-122 25
38 00
37 50
37 00

Figure 11.

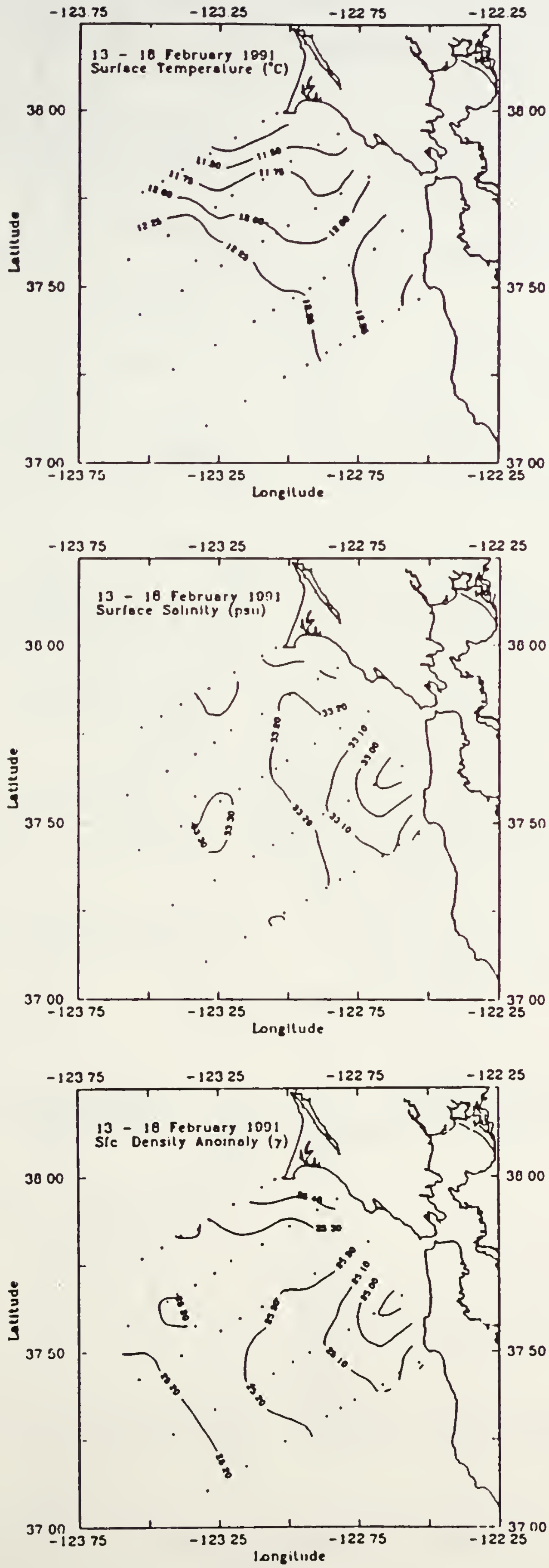

13 - 18 February 1991
Surface Temperature (°C)
13 - 18 February 1991
Surface Salinity (psu)
13 - 18 February 1991
Sfc Density Anomaly (γ)
Latitude
Longitude
38 00
37 50
37 00
-123 75
-123 25
-122 75
-122 25

Figure 12.

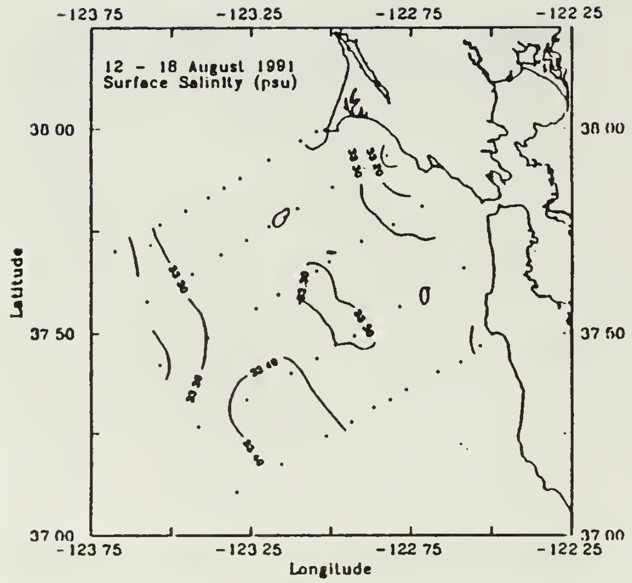


Figure 13.a.

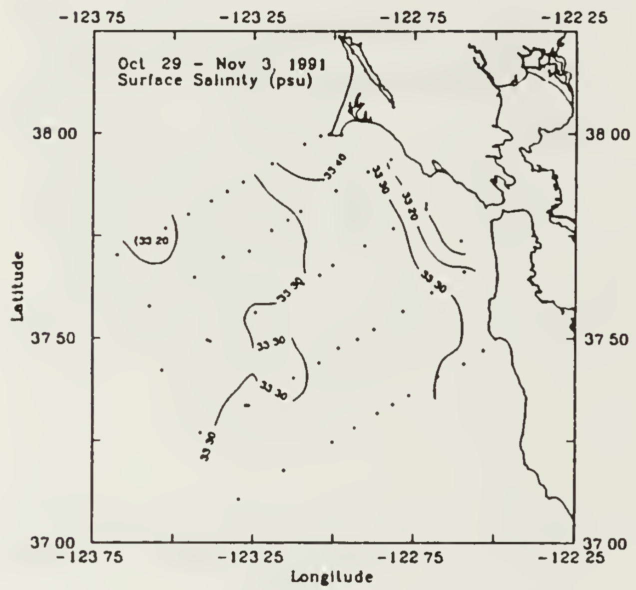


Figure 13.b.

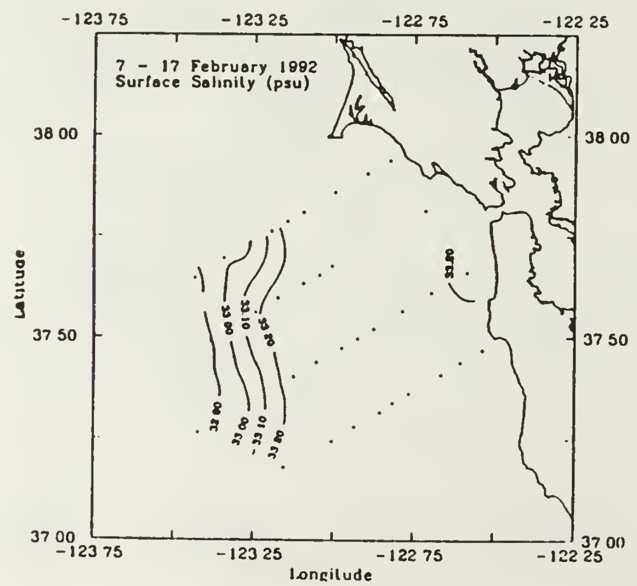
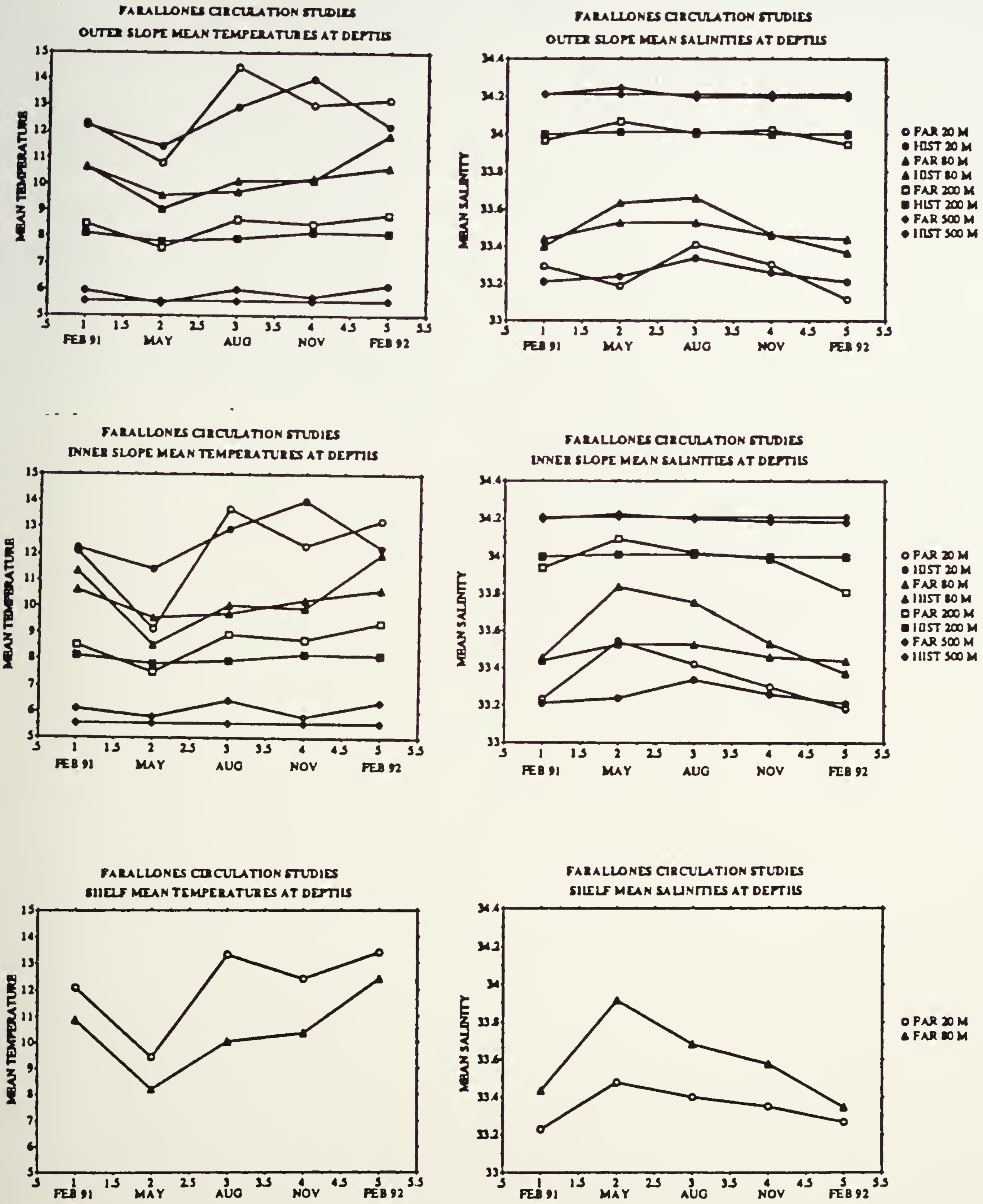


Figure 13.c.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OUTER SLOPE MEAN TEMPERATURES AT DEPTHS
MEAN TEMPERATURE
FEB 91
MAY
AUG
NOV
FEB 92
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MEAN SALINITY
FAR 20 M
HIST 20 M
FAR 80 M
HIST 80 M
FAR 200 M
HIST 200 M
FAR 500 M
HIST 500 M
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SHELF MEAN TEMPERATURES AT DEPTHS
FARALLONES CIRCULATION STUDIES
SHELF MEAN SALINITIES AT DEPTHS

Figure 14.

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